

THE EFFECTS OF SIMULATED REVERBERATION ON THE
SPEECH-PERCEPTION ABILITIES OF LISTENERS WITH NORMAL HEARING

By

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This investigation examined the effects of actual room reverberation and simulated reverberation on speech perception of listeners with normal hearing. Subjects consisted of 22 adults with normal hearing. Speech perception was assessed with the Modified Rhyme Test in actual room settings and in simulated reverberation room environments in a sound-treated IAC booth via the CATT-Acoustic software program and the Lexicon MPX-550 Effects Processor. Reverberation times were 0.5, 1.3, and 5.3 seconds. Noise competition consisted of speech-spectrum noise. Results indicated that the CATT-Acoustic reverberation simulations closely approximated the speech-perception abilities of adults with normal hearing in actual room settings, while the simulations via the Lexicon MPX-550 did not closely approximate speech perception in actual rooms. Clinical implications of these data are discussed.

CHAPTER 1 INTRODUCTION

Recent estimates suggest that over 29 million individuals in the United States exhibit some degree of sensorineural hearing loss (SNHL) (National Institutes of Deafness and Communication Disorders (NIDCD), nd; Kochkin, 2001). One of the major complications of SNHL is difficulty in communication, particularly in reverberant or noisy listening environments. Reverberation refers to the persistence or prolongation of sound as sound waves reflect off hard surfaces (e.g., walls, floors, desks, etc.) within an environment. In general, reverberation reduces speech perception due to prolongation of vowel energy. Specifically, because vowel phonemes generally are lower in frequency and higher in intensity than consonant phonemes, reverberation causes masking of the consonant sounds due to upward spread of masking. Because consonants tend to account for the vast majority of speech perception (approximately 80-90%), the masking of consonant phonemes results in reduced speech perception (French and Steinberg, 1947; Bolt and MacDonald, 1949; Gengel, 1971; Kurtovic, 1975; Finitzo-Hieber and Tillman, 1978; Gelfand and Silman, 1979; Crandell and Smaldino, 1995).

Reverberation time (RT) is often measured by the time it takes for a sound to decrease 60 dB below its initial level (or 1 millionth of its original intensity) following termination of the signal (Bolt and MacDonald, 1949; Lochner and Burger, 1964; Kurtovic, 1975; Knudsen and Harris, 1978), and is often described by the formula:

$$RT_{60} = 0.161 \left(\frac{V}{\sum S\alpha} \right)$$

where 0.161 is a constant (0.049 if feet are used), V is the volume of the room (in cubic meters) and $\sum S\alpha$ is the total absorption of surfaces in the room (Sabine, 1964).

Reverberation time is dependent on numerous factors including (1) the dimensions, shape, and volume of the room; and (2) the types, and surface areas, of absorptive and reflective materials in the room.

Reverberation time is an important determinant for speech perception. For adults with normal hearing, speech perception is not compromised until the RT exceeds approximately 1.0 second (Crum, 1974; Nabelek and Pickett, 1974a, b; Gelfand and Silman, 1979). In contrast, speech perception for listeners with SNHL is reduced when the RT exceeds approximately 0.4-0.5 second (Niemoeller, 1968; Finitzo-Hieber and Tillman, 1978; Crandell and Bess, 1986; Finitzo-Hieber, 1988; Olsen, 1988; Crandell, 1991, 1992). For example, Finitzo-Hieber and Tillman (1978) examined the effect of room acoustics on the monosyllabic word perception of 12 children with normal hearing and 12 children with hearing impairment. Three RTs (0.0, 0.4, and 1.2 seconds) were studied. Data indicated that, without noise competition (signal-to-noise ratio = ∞), children with normal hearing obtained speech-perception scores of 94.5%, 92.5%, and 76.5% for the 0.0-, 0.4-, and 1.2-seconds listening conditions, respectively. Under the same conditions, the group of children with hearing impairment obtained speech-perception scores of 87.5%, 69.0%, and 61.8%.

It has been suggested that reverberation can be simulated via models produced using computer-aided design (CAD) or via hardware-based reverberation simulators.

Computer-aided design allows the construction of a model of a three-dimensional room. The ceiling, walls, floor and furnishings of the room are drawn to scale and text files are created which contain absorption and diffusion coefficients for the various surfaces. The CAD model can then be imported into other computer programs, such as the Computer Aided Theater Technique (CATT) CATT-Acoustic program. Software such as CATT-Acoustic can allow the creation of a virtual room in which the acoustic characteristics, including RT, can be changed. Simulated reverberation programs are commonly utilized for architectural design. Such programs are critical in the design stage for building or remodeling rooms, because they enable the user to determine the sound quality of the room with different acoustic modifications, without physically making changes to the room. Rather, it is only necessary to change the absorption and diffusion characteristics for a particular surface to hear the effect of the change produced through the simulation program. For example, the change in speech-perception sound quality for carpeted floors, instead of tile floors, can be determined relatively quickly by substituting different absorption and diffusion characteristics. Computer programs that simulate reverberation are often employed in the design of concert halls in order to determine the sound quality of music in that environment.

It has also been suggested that reverberation can also be simulated via hardware-based reverberation simulators. One such instrument, the Lexicon MPX-550 Effects Processor, is a dual-channel processor. One channel consists of reverberation algorithms, while the other channel consists of delay algorithms. The Lexicon MPX-550 has 240 pre-programmed settings with reverberation algorithms such as room, chamber, plate, gate, hall, and ambiance. User-customized programs can contain up to eight adjustable

parameters. Reverberation characteristics can be adjusted via delay, pitch, and modulation effects. Hardware-based reverberation simulators are often employed in recording studios and as speaker delays for amplifying large auditoriums.

To date, there remains a paucity of data demonstrating the effect of simulated reverberation on the speech-perception abilities in listeners with normal hearing or hearing impairment. Thus, it is not known whether any of the simulations can approximate the speech perception obtained in actual rooms. In theory, the use of simulated reverberation clinically could enable the audiologist to test the effects of various RTs with the subject in the sound booth. The use of such a simulation could be important because currently there are no available clinical tests to measure the effect of reverberation on speech. Potentially, testing a patient using simulated reverberation (and/or simulated reverberation plus noise) would present a better idea of how well the patient perceives speech in "real-world" listening environments. In addition, simulated reverberation could provide additional information during hearing aid fittings, such as evaluating the function of directional microphones.

At present, only one investigation has attempted to examine the effects of simulated reverberation on speech perception (Nabelek and Robinette, 1978). This investigation used the Modified Rhyme Test (MRT) to assess speech perception in reverberation and noise. In their first experiment, subjects consisted of 5 adults with normal hearing and 7 adults with hearing impairment. Multi-talker babble served as the noise competition. Two different RTs, 0.25 to 0.50 seconds (measured in actual rooms), were assessed. This range of actual room RTs caused a significant deterioration in speech-perception scores in both groups. In specific, in the binaural condition, subjects

with normal hearing obtained speech-perception scores of 67.5% and 56.3% for the 0.25- and 0.50-seconds listening conditions, respectively. Under the same conditions, subjects with hearing impairment obtained speech-perception scores of 69.0% and 45.7%. The trend of the data indicated that as hearing loss increased, the reverberation effect decreased. Five subjects with normal hearing and 5 subjects with hearing impairment participated in the second experiment. In this experiment, a simulated reverberation was produced via a PDP-12 computer system. The computer was programmed to act as a multiple delay line, with the direct sound followed by five distinct reflections. Three different simulated RTs were assessed: 0.17, 0.44 and 0.61 second. Results indicated that with the computer-programmed simulated reverberation no significant changes in speech-perception scores were noted. Neither the difference between the mean scores of the normal-hearing and hearing-impaired groups (66.5% and 63.9%, respectively), nor the differences between mean scores for the three RTs (66.0%, 63.7%, and 65.9% for 0.17, 0.44, and 0.61 second, respectively), were statistically significant. In other words, the simulated reverberation did not emulate the actual room reverberation.

With these considerations in mind, the purpose of the present investigation was to determine the effects of simulated reverberation on the speech-perception abilities in adult listeners with normal hearing. Twenty-two adults with normal hearing served as subjects for this study. Speech perception was assessed using the MRT in actual room settings and simulated reverberation in a sound treated booth. Two reverberation simulations were used: a computer simulation utilizing the CATT-Acoustic software, and a hardware-generated simulation utilizing the Lexicon MPX-550 Effects Processor. Reverberation was simulated via both software and hardware simulations because it was

not known which may more closely approximate speech perception in actual rooms. Reverberation times were approximately 0.5, 1.3 and 5.3 seconds. The RTs of 0.5 and 1.3 seconds were representative of classroom environments. The RT of 5.3 seconds was representative of auditorium environments. Because pilot data suggested that these rooms would have ceiling effects for the speech perception of normal listeners, it was necessary to add noise ($\text{SNR} = -10 \text{ dB}$) within the 0.5- and 1.3-seconds RT rooms. This SNR would have had floor effects in the 5.3-seconds RT room, therefore a SNR of 0 dB was used in that room.

CHAPTER 2 REVIEW OF LITERATURE

Components of Sounds in Rooms

All sounds that are perceived in rooms consist of several components. These components include background noise, direct sound, early reflections, and late reflections (reverberant sound). These components of sounds are discussed below.

Background Noise

Background noise may be defined as any sound that interferes with the listeners' ability to hear the signal that they want to hear (Crandell, 1991). Noise may originate from sources outside of the building (e.g., traffic, playground, or airplane noise); from sources inside the building but outside of the room (e.g., heating, ventilation and air conditioning units, people walking and talking in the hallway, or cafeteria noise); from sources within the room (e.g., other people talking, refrigerator and garbage disposal noise if in a kitchen, or hair dryer in the bathroom); or even from sources within an individual's head (e.g., tinnitus). When speech is presented in noise, the spectral-temporal-intensity aspects of speech are distorted, resulting in decreased perception. Specifically, since consonants are lower in intensity than vowels, it is primarily the consonant phonemes that are affected, or "masked," by noise. Reduction of consonant information can severely degrade speech perception, as 80-90% of perception occurs because of consonant energy (Nabelek and Nabelek, 1994; Crandell and Smaldino, 1995). Low-frequency noise is generally more effective for masking speech than high-

frequency noise due to the upward spread of masking (Danaher and Pickett, 1975). Upward spread of masking occurs when lower-frequency sounds effectively interfere with, or “mask,” the perception of higher-frequency sounds. Noise that has the same long term spectrum of speech (e.g., speech-shaped noise or multi-talker babble) tends to be most effective at masking the speech because it affects all speech frequencies to the same degree (Nabelek and Nabelek, 1994; Crandell and Smaldino, 1995). The intensity of noise in relation to the desired speech signal is often referred to by the signal-to-noise ratio (SNR) expressed in decibels (dB). Generally, when the SNR is low, speech-perception scores are low and when the SNR is high, speech-perception scores are high (Fletcher, 1929; Kryter, 1946; Hawkins and Stevens, 1950; Licklider and Miller, 1951; Miller and Nicely, 1955; Pickett, 1957; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Nabelek and Mason, 1981; Harris and Reitz, 1985; Harris and Swenson, 1990; Nabelek and Nabelek, 1994; Johnson, 2000). In addition, individuals with hearing impairment tend to be more affected by lower SNRs than individuals with normal hearing (Crum, 1974; Nabelek and Pickett, 1974a; Finitzo-Hieber and Tillman, 1978; Harris and Reitz, 1985; Harris and Swenson, 1990; Nabelek and Nabelek, 1994; Johnson 2000). The differences in speech perception between listeners with normal hearing and hearing impairment will be discussed later in this chapter.

Direct Sound

The direct sound is the first sound to reach the listeners’ ears. Direct sound takes the shortest, or most direct, path from the speaker to the listener. Stated differently, direct sound travels from the speaker to the listener without reflecting off surfaces within

the room. The strength of the direct sound can be estimated via the inverse square law, which is defined as

$$I \propto \frac{1}{r^2}$$

where I = intensity and r = radius of a sphere (distance from sound source). The inverse square law states that in a free field, as distance doubles from the sound source, there is a 6-dB decrease in sound pressure level (SPL). The listeners will generally orient themselves to the location of the sound via direct sound. This phenomenon is known as the Law of the First Wavefront, also called the Precedence or Haas Effect (Haas, 1951). The Haas Effect states that listeners will localize a sound source based upon the direct sound if the subsequent sounds arrive within approximately 30-50 milliseconds (ms). If, however, the subsequent sounds arrive longer than 30-50 ms, then two distinct sounds are heard.

Early Sound Reflections

As speech sound propagates from its source, sound waves reflect off surfaces within the environment. The sound waves that arrive at the listeners' ears within approximately 30-50 ms of the direct sound are called early sound reflections. Early sound reflections may actually increase the perceived loudness of the sound by combining their sound energy with the direct sound (Lochner and Berger, 1964; Bradley, 1986a, b; Bradley et al., 1999). Increasing the loudness of a sound may help to improve speech perception (Nabelek and Nabelek, 1994). Stated differently, increasing the intensity of a sound will increase the SNR, thereby increasing speech-perception scores. For example, Nilsson, Soli, and Sullivan (1994) indicated that a 1-dB change in signal-to-

noise (SNR) ratio for the Hearing In Noise Test (HINT) sentences equates to a change of approximately 10% in percentage-correct scores.

Late Sound Reflections (Reverberation)

Late sound reflections, or reverberant sounds, are prolonged sound waves that arrive at the listeners' ears after approximately 50 ms. Reverberant sounds bounce off of multiple surfaces in the room while they travel from speaker to listener. Generally, the greater number of times the sound is reflected off of surfaces in the room, the less energy (loudness) that sound will have, due to the increased path distance and the partial absorption of the sound energy that occurs with each reflection off of a surface.

Reverberation is the collection of late-reflected sounds from the surfaces of a room.

Speech perception is generally reduced in the presence of reverberation due to the prolongation of vowel energy. Reverberation causes masking of consonant sounds due to upward spread of masking, because vowel phonemes generally are lower in frequency and more intense than consonant phonemes (Nabelek and Nabelek, 1994). Because consonants tend to account for the vast majority of speech perception, the masking of consonant phonemes results in reduced speech perception. Furthermore, when speech is presented at a relatively rapid rate, reverberation can cause the sound at the end of one word to overlap onto the beginning sound of the next word. That is, the pauses between words are no longer silent, but rather are filled with the reverberant energy.

Reverberation can affect not only speech perception, but also the perceived speech quality. Factors such as perceived loudness, clarity, pleasantness, noisiness of the listening environment, listening effort, acoustic comfort, acoustic intimacy, and overall impression of the sound may all vary with RT.

Reverberation Time

Reverberation time is often measured by the time it takes for a sound to decrease 60 dB below its initial level, referred to as RT_{60} . A number of factors affect RT. Such factors include: (1) the dimensions, volume, and shape of the room; and (2) the types, and surface areas, of absorptive and reflective materials in the room. Reverberation time was described by Sabine (1964) with the following formula:

$$RT_{60} = 0.161 \left(\frac{V}{\sum S\alpha} \right)$$

where .161 is a constant; V is the volume of the room in cubic meters (0.049 if measuring in feet); and $\sum S\alpha$ is the total absorption of surfaces in the room. Sabine's formula assumes that the room has relatively normal proportions and that the reverberant sound field is diffuse. For smaller rooms, such as classrooms, Sabine's formula typically underestimates RT (Kosten, 1960), because smaller rooms, such as classrooms, typically do not have diffuse reverberant fields. Therefore, in smaller rooms, RT may vary significantly as a function of the location in the room in which RT measurements were made.

Fitzroy (1959) developed a formula that may be more appropriate for estimating the RT for smaller rooms:

$$RT_{60} = \left(\frac{0.049V}{S^2} \right) \left[\left(\frac{2XY}{\alpha_{xy}} \right) + \left(\frac{2XZ}{\alpha_{xz}} \right) + \left(\frac{2YZ}{\alpha_{yz}} \right) \right]$$

where V = volume of room in cubic feet; S = surface area of the room in square feet; X = room length; Y = room width; Z = room height; and α = absorption coefficient. Fitzroy's

equation is based on calculations for the three main axes of reflections (floor to ceiling, side wall to side wall, and end wall to side wall).

Another equation for estimating RT in smaller rooms is the Norris-Eyring equation (Eyring, 1930):

$$L_p = L_w + 10 \log \left[\left(\frac{Q}{4\pi D^2} \right) + \left(\frac{4}{R} \right) \right] + 10$$

where L_p = sound pressure level in decibels; L_w = sound power level in watts; Q = the directivity of the sound source (1 = omnidirectional, 2 = hemispherical); D = distance from the sound source to the receiver; and R = room constant in Sabines of absorption ($\Sigma S\alpha$). The Norris-Eyring formula is based on an average absorption coefficient for highly absorptive rooms (Eyring, 1930). The reader is referred to Egan (1987) for detailed examples of RT using the aforementioned formulas.

Reverberation in Rooms

All rooms exhibit some reverberation. Audiometric test booths usually have RTs of approximately 0.2 second (Crandell and Smaldino, 1994). Living rooms and offices often exhibit RTs between 0.4 and 0.8 second (Nabelek and Nabelek, 1994).

Reverberation times for classrooms usually range from 0.4 to 1.2 seconds (Bradley, 1986b; Crandell, 1992; Crandell et al., 1995; Crandell and Smaldino, 2000).

Auditoriums, assembly halls and churches may have RTs in excess of 3.0 or 4.0 seconds (Crandell, 1992; Nabelek and Nabelek, 1994; Siebein et al., 1997).

Room Size and Reverberation

A difference in room size can cause different reverberation effects on speech perception. Specifically, in small rooms, all sound energy following the direct sound is

considered to be the reverberation effect (Nabelek, 1982). Stated differently, in smaller rooms, the reflections arrive at the listener's ears more rapidly and overlap. Thus, the early reflections tend to have a negligible effect on speech perception. In larger rooms (greater than approximately 300 cubic meters) the early reflections following the direct sound tend to increase speech perception, as they are more distinct and physically separated in time (Nabelek, 1982). The geometric shape of the room also is a factor for reverberation, as the angle of the surfaces will alter the angle of the reflections. The position of the speaker and the listener can also have an affect on the propagation of sound within the room (Nabelek, 1982; Crandell and Smaldino, 1995). Specifically, the location and direction that a speaker is facing and the location of the listener can influence the amount of direct versus reverberant sound that a listener receives, which in turn may impact the listener's speech-perception ability. Speech perception in noise and/or reverberation can be predicted via objective speech-perception measures or can be scored for individuals via subjective speech-perception measures. A brief summary of these measures follows. For more detailed information regarding these formulae the reader is directed to Harris (1991), Berg (1993) and Siebein et al. (1997).

Objective Speech-Perception Measures

There are a number of acoustical formulae that have been developed to estimate speech recognition in rooms of varying acoustical qualities at different locations with the room. These formulae include:

Articulation Loss of Consonants (Alcons)

The Articulation Loss of Consonants (Alcons) (Peutz, 1971) expresses the percent loss of consonant definition. The percentage of lost consonants can be calculated in the following manner for listeners within the critical distance:

$$Alcons = \left(\frac{200D^2T^2}{V} + a \right) \%$$

and for listeners beyond the critical distance as

$$Alcons = (9T + a) \%$$

where d = distance from the speaker to the listener (in meters), T = reverberation time (at 1400 Hz), V = volume of the room in cubic meters, and a = zero correction (constant for a good listener; varies between 1.5 and 12.5% for different listeners within the listening group). A high Alcons value indicates a greater loss of intelligibility. Measurements for the Alcons are based on a single 1/3-octave band centered at 2000 Hz and do not account for many factors, such as reverberation, that can dramatically reduce speech intelligibility. Therefore, the Alcons often over-estimates the intelligibility scores that would actually be obtained in reverberant environments.

Articulation Index (AI)

The Articulation Index (AI) (French and Steinberg, 1947; Fletcher and Galt, 1950) is a prediction of the perception of transmitted or processed speech. To compute the AI, the speech frequencies are divided into twenty frequency bands, usually 1/3-octave bands. Each band is assumed to contribute independently to the overall intelligibility. The SNR is computed for each band, then weighted and combined to yield the AI. Specifically, the articulation index is calculated as:

$$AI = \sum_1^n W \cdot \Delta A_m$$

where n = number of bands, ΔA_m = the maximum value of the SNR, and W = the fractional part of ΔA_m which is contributed by a band with a particular SNR (French and Steinberg, 1947). The AI is expressed as a number between 0 and 1, where an AI of 0 predicts that speech is unintelligible and an AI of 1 predicts that speech is completely intelligible.

Speech Transmission Index (STI)

The Speech Transmission Index (STI) (Houtgast et al., 1980; Steeneken and Houtgast, 1980) is a measure of speech intelligibility based on modulation transfer function (MTF) theory. The MTF is a function of modulation frequency that reflects the effect of the room (noise and reverberation) on the modulation index of a (hypothetical) test signal. The MTF function, $m(F)$, can be defined by the following equation:

$$m(F) = \left[1 + \left(2\pi F \frac{T}{13.8} \right)^2 \right]^{-1/2} \left[1 + 10^{(-S/N)/10} \right]^{-1}$$

where F = frequency and T = reverberation time (Houtgast et al., 1980). The $m(F)$ function is calculated for each of the 18 1/3-octave intervals. The 18 $m(F)$ -values are converted into 18 apparent SNRs after each $m(F)$ is clipped when exceeding the range of ± 15 dB. Hence, the STI is calculated as:

$$STI = \frac{\left[\overline{(S/N)}_{app} + 15 \right]}{30}$$

where $\overline{(S/N)}_{app}$ = the mean apparent SNR (Houtgast et al., 1980). The STI values vary from 0 to 1. A STI of 0 predicts that speech is unintelligible and an STI of 1.0 predicts that speech is completely intelligible. A special test signal that has characteristics similar

to speech is utilized in STI testing. The STI follows the concept that speech is composed of two spectra: the audible spectrum (the speech we hear) and the modulation spectrum (the frequency of phoneme production). The modulation spectrum can be represented by fourteen 1/3-octave intervals from 0.4 to about 20 Hz. The depth of the modulation of the received signal is compared with that of the transmitted signal within each band. A reduction in the modulation depth is associated with a loss of intelligibility.

Rapid Speech Transmission Index (RASTI)

The Rapid Speech Transmission Index (RASTI) (Houtgast and Steeneken, 1984) was developed as a simpler alternative to the more complex STI. Similar to the STI, RASTI values vary from 0 to 1, where 0 predicts that speech is completely unintelligible and 1 predicts that speech is completely intelligible. Likewise, RASTI uses a speech-like signal and correlates reductions in modulation depth to loss of intelligibility. Unlike the STI, however, RASTI uses only two octave bands, one centered at 500 Hz and the other centered at 2000 Hz. The calculation for RASTI is:

$$RASTI = \frac{\left[\overline{(S/N)}_{app} + 15 \right]}{30}$$

where $\overline{(S/N)}_{app}$ = the mean apparent SNR (Houtgast and Steeneken, 1984).

Direct-to-Reverberant Ratios

The quantities C_{50} and C_{80} express speech clarity as ratios between the intensity of the direct sound and the intensity of the reverberant sound (Bekesy, 1938 cited in Zahorik, 2002; Reichardt, 1972 cited in Cremer et al., 1982; Mershon and King, 1975; Mershon and Bowers, 1979). Specifically, C_{50} measures the energy ratio of the first 50

ms of direct sound to the overall steady-state reverberation, whereas C_{80} measures the first 80 ms. The formula to calculate clarity (C_{80}) is:

$$C = \log \frac{\int_0^{80\text{ms}} p^2 dt}{\int_{80\text{ms}}^{\infty} p^2 dt}$$

(Reichardt, 1972 cited in Cremer et al., 1982). The speech clarity ratio is expressed in decibels, ranging from -30 dB to +30 dB, with a minimum acceptable value of 0 dB and a preferred value of at least +4 dB.

Useful-to-Detrimental Sound Ratios

The useful-to-detrimental sound ratios express the ratio, in dB, between sounds that are useful to intelligibility and sounds that are detrimental to it (Lochner and Burger, 1964; Bradley 1986a, b; Bradley et al, 1999). Lochner and Burger (1964) suggested that early reflected sound within the first 95 ms increased speech perception (i.e., useful) whereas the reflected sound arriving after the first 95 ms reduced speech perception (i.e., detrimental). The useful-to-detrimental ratio U_{95} can be expressed as:

$$R_{95} = 10 \lg \frac{\int_0^{95} \alpha P^2 dt}{\int_{95}^{\infty} P^2 dt + P_n^2 \Delta t} \text{ dB}$$

where α = a fraction of the reflected energy relative to the direct sound (for different levels and delay times), P = the instantaneous value of the sound pressure due to the pulse, P_n = a root mean square (r.m.s.) pressure, t = time in ms, and Δt is the duration of the pulse used for measurement (Lochner and Burger, 1964). The U_{50} and U_{80} ratios are more commonly used today. Speech sounds are “useful” when they arrive within the first

50 or 80 ms after the direct sound. These sounds are perceptually integrated with the direct sound. “Detrimental” sounds are determined by adding the speech energy arriving later than 50 or 80 ms and the ambient noise in the room. For example, the U_{50} ratio, in decibels, can be described as

$$U_{50} = 10 \log \left(\frac{E_d + E_e}{E_l + E_n} \right)$$

where E_d = the direct energy from the speaker, E_e = the early arriving, reflected energy from the speaker, E_l = the late-arriving reflected energy, and E_n = noise energy (Hodgson and Nosal, 2002).

Subjective Speech-Perception Measures

In addition to objective measures that estimate speech perception, subjective measures can be used to obtain actual samples of listeners’ perception of speech within a given environment. Speech stimuli in such subjective measures consist of syllables, words, and sentences. Table 1 shows examples of some commonly available speech-perception tests. It should be noted that each of these speech-perception tests can provide the investigator with different and pertinent aspects of the perceptual effects of reverberation on speech perception. In contrast to tests containing syllabic stimuli, tests utilizing word and sentence stimuli may provide more “real-world” contextual information regarding perceptual processes due to their higher linguistic content. A number of studies utilizing subjective speech-perception measures have been conducted to evaluate the effects of reverberation on various groups of listeners.

Effects of Reverberation on Listeners with Normal Hearing

Speech perception can be influenced greatly by RT. Adults with normal hearing appear to not experience difficulties with RTs between 0-1 second, but demonstrate diminished speech perception above approximately 1.0 second (Crum, 1974; Finitzo-Hieber and Tillman, 1978; Gelfand and Silman, 1979). For example, Crum (1974) studied the effects of reverberation, noise, and distance from the speaker on the monosyllabic speech perception of adults with normal hearing. Reverberation times (averaged over 500, 1000, and 2000 Hz) were 0.0, 0.4, 0.8 and 1.2 seconds. Speech stimuli consisted of ten revised 50-word lists of consonant-nucleus-consonant (CNC) words (Peterson and Lehiste, 1962). Signal-to-noise ratios (SNRs) were $+\infty$, +6, and 0 dB. Speaker-to-listener distances of 6, 12, and 24 feet were evaluated. The signal level was calibrated to 70 dB SPL at 6 feet. Results indicated that distance had no effect on speech perception in the RT = 0.0-second (anechoic) condition. In the reverberant conditions, speech-perception scores dropped significantly from 6 to 12 feet, but did not differ between 12 and 24 feet. Speech perception in quiet (SNR = $+\infty$ dB) was essentially unchanged from 0.0- to 0.8-second RT; however, at the 1.2-seconds RT, speech perception decreased. Furthermore, the data suggested the combination of reverberation, noise, and distance interacted in a significant manner. In specific, the combination of these factors caused a greater reduction in speech perception than would be predicted by summing the effects of each variable individually. A summary of the data is shown in Table 2.

Nabelek and Pickett (1974a, b) assessed the effect of noise and reverberation on monaural and binaural speech perception through ear-level hearing aids for listeners with

normal hearing. Five subjects with normal hearing participated. The MRT served as the speech stimuli. The level of the speech, measured at the point occupied by the subject's head, was 50 dB (B-weighting). Noise competition consisted of an eight-person multi-talker babble (consisting of 4 female and 4 male voices). Speech stimuli and noise competition were presented through loudspeakers located 11 feet from the subject at ± 30 degrees azimuth. The signal-to-noise ratio (SNR) varied from the quiet condition (+35 dB) to -15 dB. Reverberation times (averaged for 500, 1000, and 2000 Hz) were 0.3 and 0.6 second. The RT was altered by changing the absorption characteristics of the room. A summary of the data is shown in Table 3. Contrary to findings in other studies, results indicated that speech perception was significantly decreased for listeners with normal hearing as the RT increased from 0.3 to 0.6 second.

Finitzo-Hieber and Tillman (1978) examined the effect of room acoustics on the monosyllabic speech perception of 12 children with normal hearing between the ages of 8-12 years old. Three RTs (0.0, 0.4, and 1.2 seconds) were studied. Speech-perception scores for the 0.0-second RT were measured in an anechoic chamber. An acoustically-modified reverberant chamber was used the 0.4- and 1.2-seconds RT. Each room had a volume of approximately 162 cubic meters (6000 cubic feet). Speech stimuli consisted of six of the 10 Peterson-Lehiste CNC lists (Peterson and Lehiste, 1962). Each list consisted of 50 monosyllabic words. Subjects were seated 12 feet from the loudspeaker at 0 degrees azimuth. Results are shown in Table 4. Data indicated that, without noise competition (signal-to-noise ratio = ∞ dB), children with normal hearing obtained speech-perception scores of 94.5%, 92.5%, and 76.5% for the 0.0-, 0.4-, and 1.2-seconds listening conditions, respectively. With a SNR of 0 dB under the same listening

conditions, the scores were 60.2%, 47.7%, and 29.7%, respectively. The results suggested that reverberation and noise when presented together have a more detrimental effect on speech perception than when either reverberation or noise is presented alone.

Gelfand and Silman (1979) examined the effects of small room (1.83x 1.60 x 2.34 meters) reverberation upon on phoneme recognition by 20 subjects with normal hearing. The MRT was used as speech stimuli. The MRT was played in a room with an RT of 0.8 second (averaged for 500, 1000, and 2000 Hz) and recorded in order to make a reverberant recording. Subjects were tested in a sound-treated booth under supraaural headphones. The recording of the MRT in quiet and the reverberant recording of the MRT were presented to the subject. The presentation level was 50 dB SPL. Subjects listened to 10 subtests (5 for initial consonants and 5 for final consonants) of the MRT, presented in a random order. A summary of the data is shown in Table 5. Results indicated that speech perception in the quiet condition was better than in the reverberant condition and that speech perception for initial consonants was better than for final consonants. The authors postulated that the reduction in consonant recognition appeared to be due to the multiple reflections essentially acting as speech-shaped noise. These data suggested that the phonetic features of place, stop, and frication were most affected by reverberation.

Harris and Reitz (1985) investigated the effect of reverberation and noise on speech perception in the elderly. Speech perception was measured in a sound field for a group of college-aged listeners with normal hearing (mean pure tone average (PTA) < 6 dB HL) and a group of "normal-hearing" elderly listeners (mean PTA = 9.9 dB HL). Room conditions included a sound suite and a reverberant room with different levels of

absorptive materials (RT = 0.59 and 1.56 seconds, averaged at 500, 1000, and 2000 Hz). Speech perception was assessed in quiet and speech-spectrum noise (SNR = +10 dB) via Central Institute for the Deaf (CID) W-22 word lists. Results, shown in Table 6, indicated that speech perception decreases as reverberation increases. Both groups did similarly well in the sound suite in both quiet and noise, as well as in both reverberation conditions in quiet. However, when noise was added to the reverberant conditions, the elderly “normal-hearing” subjects’ speech perception declined faster than the normal-hearing subjects. These results indicated that the elderly “normal-hearing” may experience more difficulties in real-world listening conditions, where both noise and reverberation are common, than the younger group with normal hearing. Such elderly people may report having difficulty in everyday communication environments; however, traditional speech-perception testing would not reveal this difficulty.

Nabelek and Letowski (1986) also assessed the effects of noise and reverberation on speech perception. Ten adults with normal hearing served as subjects. Speech stimuli consisted of CVC syllables. One consonant and the vowel were held constant and the other consonant was variable. The consonant /t/ was constant and the vowels were /a/ and /i/. Tests were recorded without and with reverberation. Reverberation times were 0.0 and 1.2 seconds (averaged at 500, 1000, and 2000 Hz). The 1.2-seconds reverberation recording was made in a room with a volume of 165 cubic meters. Noise stimuli consisted of multitalker babble (12 voices). A SNR of +5 dB was used for the noise conditions. The results of this study are shown in Table 7. Results suggested that speech perception in quiet was better than speech perception in noise or reverberation. Overall, the data suggested that speech perception of the initial consonant was better than

speech perception of the final consonant for the quiet, noise, and reverberation conditions. It should be noted that this difference in consonant position speech perception may be dependent on the vowel in the reverberation condition. In specific, speech-perception scores for the initial consonant position were 11.3% better than speech-perception scores for the final consonant position for the vowel /a/, but were 7.7% worse for the vowel /i/.

Johnson (2000) examined the effects of reverberation and noise on listeners' identification of consonants and vowels at various sensation levels (SLs) relative to the speech recognition level (SRT). Eighty subjects were divided into 4 age groups of 10 males and 10 females. The age groups were 6-7 years old, 10-11 years old, 14-15 years old, and adults (18-30 years old). The speech stimuli were List A of the Nonsense Syllable Test (NST) (Edgerton and Danhauer, 1979), a 25-item, consonant-vowel-consonant-vowel test of phoneme identification. The four listening conditions were quiet (no noise or reverberation), reverberation only (RT = 1.3 seconds, averaged at 500, 1000 and 2000 Hz), noise only (SNR = +13), and reverberation plus noise. The noise competition consisted of multitalker babble. Sensation levels were 30, 40, 50, and 60 dB SL (re: SRT). Results are shown in Table 8. These results suggested a difference between the groups' abilities to identify consonants as a function of listening condition. Generally, as age increased from young child to adult, the speech-perception abilities increased, suggesting a differential maturation of consonant abilities. Data for all groups suggested that speech-perception scores in reverberation or noise were lower than speech-perception scores in quiet. Furthermore, speech-perception scores for the reverberation plus noise condition were poorer than all other listening conditions. These

scores suggest a synergistic effect of reverberation and noise. Stated differently, reverberation and noise when presented together have a more detrimental effect on speech perception than when either reverberation or noise is presented alone.

Effects of Reverberation on Listeners with Hearing Impairment

In contrast to individuals with normal hearing, speech perception for listeners with SNHL is reduced when the RT exceeds approximately 0.4-0.5-second (Niemoeller, 1968; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Harris and Reitz, 1985; Nabelek and Letowski, 1985; Crandell and Bess, 1986; Finitzo-Hieber, 1988; Olsen, 1988; Harris and Swenson, 1990; Crandell, 1991, 1992). Nabelek and Pickett (1974a, b) examined the effect of noise and reverberation on monaural and binaural speech perception through ear-level hearing aids for listeners with hearing impairment. Five subjects with SNHL participated. The MRT served as the speech stimuli. The level of the speech, measured at the point occupied by the subject's head, was 60 dB (B-weighting). Noise competition consisted of an eight-person multi-talker babble (consisting of 4 female and 4 male voices). Speech stimuli and noise competition were presented through loudspeakers located 11 feet from the subject at ± 30 degrees azimuth. The signal-to-noise ratio (SNR) varied from the quiet condition (+35 dB) to -15 dB. Reverberation times (averaged for 500, 1000, and 2000 Hz) were 0.3 and 0.6 second. The RT was altered by changing the absorption characteristics of the room. Results indicated that speech perception was significantly decreased for subjects as the RT increased from 0.3 to 0.6 second. Significantly, the group with SNHL did not perform as well at lower SNRs as the group with normal hearing. Results for the aided conditions suggested that speech perception deteriorated as the SNR decreased for both RTs;

however, the overall size of deterioration was smaller for the RT of 0.6 second compared to the shorter RT of 0.3 second.

Finitzo-Hieber and Tillman (1978) examined the effect of room acoustics on the monosyllabic word perception of 12 children with hearing impairment between the ages of 8-13. Three RTs (0.0, 0.4, and 1.2 seconds) were studied. Speech-perception scores for the 0.0-second RT were measured in an anechoic chamber. An acoustically-modified reverberant chamber was used the 0.4- and 1.2-seconds RT. Each room had a volume of approximately 162 cubic meters (6000 cubic feet). Speech stimuli consisted of six of the 10 Peterson-Lehiste CNC lists (Peterson and Lehiste, 1962). Each list consisted of 50 monosyllabic words. Subjects were seated 12 feet from the loudspeaker at 0 degrees azimuth. Results are shown in Table 4. Data indicated that, without noise competition (signal-to-noise ratio = ∞ dB), children with hearing impairment obtained speech-perception scores of 87.5%, 69.0%, and 61.8% for the 0.0-, 0.4- and 1.2-seconds listening conditions, respectively. With a SNR = 0 dB, scores for the same listening conditions were 42.2%, 28.8%, and 15.3%, respectively. The results suggested that reverberation and noise when presented together have a more detrimental effect on speech perception than when either reverberation or noise is presented alone.

Harris and Reitz (1985) examined the effect of reverberation and noise on speech perception in the elderly. Speech perception was measured in the sound field for a group of elderly listeners with hearing impairment. Reverberation times were approximately 0.0, 0.59 and 1.56 seconds (averaged at 500, 1000, and 2000 Hz). Speech perception was assessed in quiet and speech-spectrum noise (SNR = +10 dB) via CID W-22 word lists. These results suggested that mean speech-perception scores for elderly listeners with

hearing impairment decreased more rapidly than their elderly normal-hearing counterparts under reverberation plus noise conditions. Overall, results from this study suggest that the deleterious effects of reverberation and noise on speech perception increase as age increases, regardless of the presence of hearing loss.

Nabelek and Letowski (1985) evaluated the effects of reverberation on the perception of diphthongs and vowels in 10 adults with moderate degrees of SNHL. Fifteen vowels and diphthongs of the English language were recorded in the syllable /b—t/ by a male talker using the carrier phrase, “Mark the /b—t/ again.” Tests were recorded without and with reverberation. Reverberation times were 0.0 and 1.2 seconds (averaged at 500, 1000, and 2000 Hz). The 1.2-seconds reverberation recording was made in a room with a volume of 165 cubic meters. Subjects were tested monaurally in the better ear under headphones in a sound-treated booth. Results, shown in Table 9, suggested that speech-perception scores for all subjects were better in the condition with no reverberation than in the condition with reverberation. Large individual differences between subjects were noted, which suggested a large variation of the speech-perception abilities among subjects. In other words, it appears that subjects with approximately the same degree of hearing sensitivity may have very different speech-perception abilities.

Harris and Swenson (1990) examined the speech-perception abilities of adults with various degrees of SNHL. Subjects were assigned to one of three groups, consisting of 10 subjects each: (1) normal hearing; (2) mild SNHL; and (3) moderate-to-severe SNHL. Reverberation times were approximately 0.0, 0.54 and 1.55 seconds (averaged at 500, 1000, and 2000 Hz). Speech perception was assessed in quiet and speech-spectrum noise (SNR = +10 dB) via CID W-22 word lists. Results are displayed in Table 10.

These results indicate that speech perception decreased for all subjects as reverberation and/or noise increased; however, the speech-perception abilities were poorer as the hearing sensitivity decreased. Furthermore, results suggested that the subjects with hearing impairment were much more affected by minimal increases in RT when listening to speech in the presence of background noise than were the subjects with normal hearing.

Effects of Reverberation on Listeners with Hearing Aids

Nabelek and Pickett (1974a, b) examined the effect of noise and reverberation on monaural and binaural speech perception through ear-level hearing aids for listeners with normal hearing. Five subjects with normal hearing and five subjects with hearing impairment participated. The MRT served as the speech stimuli. The level of the speech, measured at the point occupied by the subject's head, was 50 dB and 60 dB (B-weighting) for listeners with normal hearing and SNHL, respectively. Noise competition consisted of an eight-person multi-talker babble (consisting of 4 female and 4 male voices). Speech stimuli and noise competition were presented through loudspeakers located 11 feet from the subject at ± 30 degrees azimuth. The signal-to-noise ratio (SNR) varied from the quiet condition (+35 dB) to -15 dB. Reverberation times (averaged for 500, 1000, and 2000 Hz) were 0.3 and 0.6 second. The RT was altered by changing the absorption characteristics of the room. Results for the aided conditions suggested that speech perception deteriorated as the SNR decreased for both RTs; however, the overall size of deterioration was smaller for the RT of 0.6 second compared to the shorter RT of 0.3 second.

Finitzo-Hieber and Tillman (1978) examined the effect of room acoustics on the monosyllabic word perception of 12 children with hearing impairment between the ages of 8-13. Three RTs (0.0, 0.4, and 1.2 seconds) were studied. Speech-perception scores for the 0.0-second RT were measured in an anechoic chamber. An acoustically-modified reverberant chamber was used the 0.4- and 1.2-seconds RT. Each room had a volume of approximately 162 cubic meters (6000 cubic feet). Speech stimuli consisted of six of the 10 Peterson-Lehiste CNC lists (Peterson and Lehiste, 1962). Each list consisted of 50 monosyllabic words. Subjects were seated 12 feet from the loudspeaker at 0 degrees azimuth. Results, shown in Table 4, suggested that without noise competition (signal-to-noise ratio = ∞ dB), aided speech-perception scores were 83.0%, 60.2%, and 45.0% for the 0.0-, 0.4- and 1.2-seconds listening conditions, respectively. With a SNR = 0 dB, aided scores for the same listening conditions were 39.0%, 27.8%, and 11.2%, respectively. The results suggested that reverberation and noise when presented together have a more detrimental effect on aided speech perception than when either reverberation or noise is presented alone.

Nabelek and Mason (1981) measured the effects of both noise and reverberation on the speech perception of individuals with bilateral SNHL. The MRT served as the speech stimuli. A multi-talker babble (10 female and 10 male voices) served as the noise competition. Reverberation times were 0.1 and 0.5-second, averaged over 500, 1000, and 2000 Hz. Twenty-one subjects (ages 21-81 years) participated. Subjects had mild to moderate bilateral SNHL and various audiometric contours. Subjects were tested in unaided and aided conditions, both monaurally and binaurally. Signal-to-noise ratios varied from quiet (approximately +30 dB) to -5 dB. The speech and noise competition

were presented from two loudspeakers located 2 meters from the subject's head at ± 30 degrees azimuth. Results from this study, summarized in Table 11, indicated significant differences between the speech-perception scores for the two RTs, for unaided and aided listening, and for monaural and binaural listening. For example, the unaided binaural speech-perception scores in quiet were 85.1% and 69.0% for the 0.1- and 0.5-second RT, respectively. For the 0.5-second RT, unaided speech-perception scores quiet were 62.7% and 69.0% for monaural and binaural, respectively, whereas, aided speech-perception scores were 73.3% and 78.5%, respectively. In contrast, unaided speech-perception scores for the 0.5-second RT with a SNR = +5dB were 26.8% and 31.4% for monaural and binaural, respectively, and aided speech-perception scores were 28.8% and 32.1%, respectively. A trend of speech-perception scores declining as SNR declined was also noted. The combined effect of noise and reverberation was greater than the sum of the effects.

Leeuw and Dreschler (1991) investigated the effect of reverberation and noise on normal-hearing listeners fitted with hearing aids. Twelve subjects were tested with omnidirectional and directional microphones. Speech recognition thresholds (SRTs) were established using an adaptive procedure. In Experiment A, speech stimuli were presented at 0 degrees azimuth. Noise was presented at 0, 45, 90, 135, and 180 degrees azimuth. Rooms with RTs (averaged over the octave bands from 500-2000 Hz) of 0.156 second ("dead" room) and 0.883 second ("reverberant" room) were used. The subject was seated at 1.4m from the loudspeakers. This distance was within and beyond the critical distance for the dead and reverberant rooms, respectively. Subjects were fitted monaurally with hearing aids, with the non-amplified ear sealed with an earplug. Results

are summarized in Table 12. In the dead room, no difference between microphone types was noted with noise at 0 degrees azimuth. The difference increased as the azimuth increased to 180 degrees, where a 4 dB increase in SRT was noted (directional lower than omnidirectional). Recall that a lower SRT indicates better speech perception. In the directional room, the differences between microphone types were independent of the azimuth of the noise. The mean SRT difference for five noise directions was 2 dB (directional lower than omnidirectional). Overall, nine of the ten SRT values were better for the dead room. In Experiment B, only the reverberant room and the monaural condition were evaluated. Speech stimuli were presented at 0 degrees azimuth and noise was presented at either 0 degrees or 180 degrees azimuth, depending on subject group. Subjects were assigned either a directional or omnidirectional hearing aid seated in one of two positions. The first position was within the critical distance (0.5 meters from the front speaker and 2.3 m from the rear speaker) and the second position was outside of the critical distance (1.4 m from both speakers). Results of Experiment B are summarized in Table 13. These results indicated that SRTs with the directional microphone were lower than with the omnidirectional microphone in all conditions. The difference was smaller when noise was presented at 0 degrees azimuth. The difference was smaller still when the subjects were within the critical distance. The difference in mean SRT values between hearing aids was statistically significant ($p < .01$). Neither the effect of distance nor the influence of azimuth was statistically significant, although this may be explained by the small sample size. Experiment C looked at the effects of binaural fitting. Not surprisingly, the overall results indicated that the SRTs for the binaural conditions were approximately 2.5 dB lower compared to the monaural conditions in Experiment A. This

improvement in SRTs is consistent with the concept of binaural summation, i.e., the use of two ears will result in approximately a 3 dB improvement of SRT as compared to the use of one ear.

Simulated Reverberation

Simulated Reverberation and Music

As previously stated, several studies have evaluated the effect of simulated reverberation on music (Gold, 1994; Morimoto, Iida, Sakagami, and Marshall, 1994; Soulodre and Bradley, 1994). For example, Gold (1994) examined the importance of lateralization for the subjective evaluation of spatial impression. The sound source was a “dry,” or anechoic (containing no reverberation or room effects) recording of a classical string quartet piece. Sound reflections and reverberations were created via Lexicon LXP-5 effects processing modules. These elements were combined into a binaural signal with a Mackie audio mixing console and recorded on digital audio tape. Virtual sound fields were randomized and presented via Sony MDR V600 stereo headphones. A summary of configurations of virtual sound fields is shown in Table 14. Subjects were divided into three groups in order to evaluate the effects of overall listening level. Specifically, group 1 consisted of 26 subjects who evaluated 22 sound fields at 60 dBA. Groups 2 consisted of 33 subjects who evaluated 15 sound fields at 66 dBA. Group 3 consisted of 39 subjects who evaluated 15 sound fields at 71 dBA. Group 1 evaluations of spatial impression did not have any statistical differences (except for the anechoic condition). This finding may have been due to a relatively high background noise level (49 dBA) combined with the reflections and reverberation being -10 dB relative to the direct sound. In other words, much of the “spatial” auditory information was masked by the

background noise as it fell below the level of background noise. Group 2 evaluations yielded significant differences between many of the virtual fields. There also were significant differences between many of the virtual sound fields between groups 1 and 2. Group 3 ratings were similar to group 2, indicating that the additional increase in loudness from 66 to 71 dBA did not have a significant effect on the individual sound fields. Further results from groups 2 and 3 indicated that the perceived sense of spatial impressions was increased by lateral sound reflections. It was concluded that sound fields with reverberation were rated as producing a greater sense of spatial impression than sound fields containing both lateral reflections and reverberation. It is possible that the presence of early reflections masked the reverberant field. Furthermore, a greater sense of spatial separation was achieved by lateral reverberation than centered reverberation, suggesting that a completely diffuse reverberant environment would not be desirable in an auditorium if a sense of spatial impression is a goal. See Table 15 for a summary of the data from group 2.

Soulodre and Bradley (1994) used anechoic music as the stimulus to examine the influence of late arriving energy on concert hall spatial impression. All measurements were made in an anechoic chamber. Sound fields were generated via three loudspeakers located at 0 and ± 45 degrees azimuth. A custom-built hardware-based system added reverberation and delay. The amount of reverberation and delay to each loudspeaker were independently controlled. Nine subjects participated in the study. Subjects were given a paired-comparison task, in which they were presented with pairs of sound fields in random order and switched back and forth between the two sound fields until they made their judgment. The first experiment examined how reverberation affected a

listener's ability to detect changes in early lateral energy; the lateral sound arriving at the listener within the first 80 ms. Reverberation was calculated using C_{80} , or "80 milliseconds clarity," which is the difference of the energy (in dB) for the time range 0 to 80 ms as against 80 ms to infinity. Sound impression is clearer for larger values of C_{80} , meaning the signal is hardly disturbed by later arriving diffuse sound (ISO3382, 1997). Subjects were asked to identify which of the paired sound fields they perceived as wider. Results, shown in Table 16, indicated that subjects were able to correctly judge the widths of the sound fields when no reverberation was added; however, the number of subjects who made errors increased as RT increased. The results of this first experiment suggested that as reverberation increased, the number of subjects who made error also increased. Stated differently, subjects were less accurate in detecting changes in early lateral energy in the presence of reverberation. In the second experiment, subjects judged the difference in perceived source width (between the two sound fields) on a five-point scale, with 1 indicating the two widths were "the same," and 5 indicating that the widths were "very different." Subjects detected changes in lateral fraction (LF) of 0.07 without reverberation ($C_{80} = 30\text{dB}$) and 0.22 with reverberation ($C_{80} = 2.5\text{dB}$). A lateral fraction shows the share of sound energy that arrives during the first 80 ms from lateral directions (ISO3382, 1997). A higher LF indicates that more sound energy arrived from lateral directions (as compared to sound energy that arrived from the front). Results, shown in Table 17, confirmed the findings of the first experiment. For the third experiment, subjects judged differences in listener envelopment, or "the sense of feeling surrounded by the sound or immersed in the sound," (Soulodre and Bradley, 1994, p. 103). The direct sound and four early reflections were held constant, while the reverberant tail used

in the first two experiments was replaced with a gated burst of energy. Delay times of 0, 80, and >100 ms were used. The gated burst was 70 ms, and was either presented at -6 dB or -1 dB relative to the combined energy of the direct sound and early reflections. One sound field (0 ms delay, -6 dB) was used as the reference and was paired with the other sound fields. A 5-point scale was used. Results (shown in Table 18) indicated that listeners felt more enveloped when the gated burst arrived after 80 ms. Delays larger than 80 ms and higher levels of gated burst increased the sense of listener envelopment. It has been suggested that apparent source width and listener envelopment are components of spatial impression. Results of these experiments indicated that apparent source width is influenced by early lateral reflections and is more difficult to determine as RT increases, whereas listener envelopment is produced by later-arriving energy and is influenced by arrival time and intensity of the later energy. Thus, it appears that in order for a listener to have a more complete sense of spaciousness in a concert hall, it may be necessary to have both early and later reflections arriving from the sides of the listener.

Simulated Reverberation and Speech Perception

As previously noted, there remains a paucity of empirical data demonstrating the effect of simulated reverberation on speech perception. Nabelek and Robinette (1978) assessed the effects of real room RT, simulated reverberation, and noise on speech perception. This study consisted of two experiments. In the first experiment, speech stimuli consisted of the MRT. The noise competition consisted of a multi-talker babble of 4 male and 4 female talkers reading different texts simultaneously. Stimuli were presented through loudspeakers located 6 feet (1.83 meters) from the subject at ± 30 degrees azimuth. Subjects consisted of 5 individuals with normal hearing (age range =

22-40 years; mean = 34 years) and 7 individuals with bilateral SNHL (age range = 17-65 years; mean = 43 years). Subjects were tested in a sound-treated room that was acoustically modified to change the RT. The RT (averaged at 500, 1000, and 2000 Hz) of the room without acoustical modifications was 0.25 second. With Masonite panels covering the walls and ceiling, the room RT was 0.50 seconds. For subjects with normal hearing, the speech stimuli were presented at 50 dB SPL with a SNR of -5 dB. For subjects with hearing impairment, the speech stimuli were presented at the most comfortable level (MCL) and the SNR was adjusted to produce speech-perception scores approximately 20 percent lower than the best scores for the same subject with RT = 0.25 second. The individually-determined SNR remained constant during all tests. Results indicated that this range of actual room RTs caused a significant deterioration in word recognition scores for both groups of subjects. In specific, in the binaural condition, subjects with normal hearing obtained speech-perception scores of 67.5% and 56.3% for the 0.25- and 0.50-second listening conditions, respectively. Under the same conditions, subjects with hearing impairment obtained speech-perception scores of 69.0% and 45.7%.

In the second experiment, simulated reverberation was produced via a PDP-12 computer system. The PDP-12 was programmed to act as a multiple delay line. The MRT lists were recorded on magnetic tapes as a direct sound followed by five distinct reflections with time delays. The first reflection had the same amplitude as the direct sound and the other reflections decreased by 6 dB per reflection over a time period approximately equal to 40% of the RT that they were simulating. Computer-simulated RTs were 0.17, 0.44, and 0.61 second. The remaining methodology was the same as the

testing in actual rooms. Results of this experiment indicated there were no significant changes in speech-perception scores between the simulated RT conditions. In other words, the simulated reverberation did not emulate the actual room reverberation. In specific, in the binaural condition, subjects with normal hearing obtained speech-perception scores of 65.0%, 62.6%, and 65.9% for the 0.17-, 0.44- and 0.61-second listening conditions. Under the same conditions, subjects with hearing impairment obtained speech-perception scores of 69.0%, 69.4%, and 72.5%. The authors discussed the clinical implications of using speech-perception tests produced via simulated reverberation. Specifically, actual reverberation might be more complicated than the simulated reverberation due to the expense of the test room and time needed to change conditions. At the present time, speech-perception tests utilizing simulated reverberation are not available.

Gordon-Salant and Fitzgibbons (1993, 1995a, b) examined the effects of simulated reverberation on speech perception of young and elderly listeners. Four groups of subjects were examined: (1) young, normal hearing; (2) young, hearing-impaired; (3) elderly, normal-hearing; and (4) elderly, hearing-impaired. Speech stimuli were the low-predictability (LP) sentences of the Revised Speech Perception in Noise test (R-SPIN). The speech stimuli were presented in undistorted form and three forms of temporal distortion (time-compression, reverberation, and interruption). Reverberation times were 0.0, 0.2, 0.3, 0.4, and 0.6 second. Reverberant speech was created via software based on the image method for simulating small-room acoustics. Gordon-Salant and Fitzgibbons (1993) stated that the room model assumed a rectangular area. A time-domain image expansion method was utilized to calculate a transfer function (i.e., a source-to-receiver

impulse response). The impulse response was calculated by inputting the number of impulse points, the source and receiver locations, the room dimensions, and the reflection coefficients of the walls, ceiling, and floor. Reverberation time was then estimated via an energy decay curve for the impulse response. A Fast-Fourier Transform (FFM) method was used to convolve an anechoic speech sample with a calculated impulse response, thus creating a reverberant speech sample. (Gordon-Salant and Fitzgibbons, 1993).

Results of this study indicated that speech recognition of the undistorted stimuli was affected by hearing loss but not by age. Hearing loss and age were both significant variables affecting speech recognition in reverberation (see Table 19). It should be noted that the speech-perception results obtained for the simulated reverberation were not compared to results from any actual rooms. Therefore, it is difficult to conclude that the results of these studies utilizing simulated RT actually approximated the subjects' speech perception in "real-world" reverberation.

With these considerations in mind, the purpose of the present investigation was to determine the effect of simulated reverberation on speech perception in adults with normal hearing. In order to achieve this purpose, four factors were examined: room environment, noise competition, reverberation, and consonant position. The three levels of room environment were actual rooms, CATT-Acoustic simulations, and Lexicon MPX-550 simulations. The two levels of noise competition were without and with added noise. The three levels of reverberation were RTs of approximately 0.5, 1.3, and 5.3 seconds. The two levels of consonant position were speech-perception scores for initial consonant and final consonant positions.

Experimental Questions and Hypotheses

With these considerations in mind, the purpose of this investigation was to examine the effects of simulated reverberation on the speech-perception abilities of adult listeners with normal hearing. Because there is limited empirical data comparing speech-perception abilities in simulated reverberation versus actual rooms, this study examined 18 different conditions, which are discussed in detail in the next chapter. If speech-perception scores in reverberation can be simulated, a simulated reverberation CD may be made commercially available that would allow audiologists to change the RT simply by changing tracks on the CD. Speech-perception scores could be plotted as a function of RT, or an adaptive procedure might be used that would increase the RT if the individual responded correctly and decrease the RT if the individual responds incorrectly. More complex stimuli, such as sentences, would be useful to incorporate into such a test. A simulated reverberation test would be clinically useful in testing a variety of populations such as individuals with normal hearing, individuals with hearing loss, children, individuals with APD, and individuals who speak English as a second or other language (ESOL). In addition, such a test may be used to evaluate the benefit of directional hearing aid microphones in real-world conditions.

Twenty-two adults with normal hearing, between the ages of 18 and 28 years old, served as subjects. Specifically, the following experimental questions were examined:

- (1) Can speech-perception scores for one or both simulations (either CATT-Acoustic, Lexicon MPX-550) predict speech-perception scores in the actual rooms? This was the major experimental question of this investigation.
- (2) Is speech-perception ability affected by reverberation?
- (3) Is speech-perception ability affected by noise?

- (4) Is speech-perception ability affected greater by the combination of reverberation and noise than by either factor alone?
- (5) Is speech perception of initial consonants different than speech perception of final consonants in the presence of reverberation and/or noise?

Several hypotheses were formed for this experiment. The null hypothesis (H_0) is stated as all levels of the factor are equal. The alternative hypothesis (H_a) is stated as not all levels of the factor are equal. A brief explanation and formal statement of each hypothesis follows.

Room Environment

The factor of room environment compares the speech-perception scores for the actual rooms with the speech-perception scores for the CATT-Acoustic simulations and Lexicon MPX-550 simulations. In order for the null hypothesis to be accepted, all three room environments cannot be statistically different. If the room environments are statistically different then the null hypothesis is rejected in favor of the alternative hypothesis.

H_0 : Actual Room = CATT-Acoustic = Lexicon MPX-550.

H_a : Not all room environments are equal.

Noise Competition

The factor of noise competition compares the speech-perception scores for the conditions without added noise (quiet) to the conditions with added noise. If the quiet and noise levels of this factor are not statistically different then the null hypothesis would be accepted. If there is a difference between the two levels then the alternative hypothesis would be accepted.

Ho: Quiet = Noise.

Ha: Quiet $\neq$ Noise.

Reverberation

The factor of reverberation compares the three RTs of 0.5, 1.3, and 5.3 seconds. For the purposes of this study, these three RTs are referred to as the short RT, medium RT, and long RT, respectively. If the speech-perception scores for all three RTs are not statistically different then the null hypothesis would be accepted. If, however, speech-perception scores for at least one of the RTs are different then the alternative hypothesis would be accepted.

Ho: Short RT = Medium RT = Long RT.

Ha: Not all RTs are equal.

Consonant Position

The factor of consonant position compares the speech-perception scores for initial consonants versus final consonants. If these scores are not statistically different, the null hypothesis will be accepted. The alternative hypothesis will be accepted if these scores are different statistically.

Ho: Initial = Final.

Ha: Initial $\neq$ Final.

Table 1. Commonly available speech-perception tests.

Syllables	Words	Sentences
Edgerton-Danhauer Nonsense Syllable Test (NST)	Northwestern University Auditory Test Number 6 (NU-6)	Synthetic Sentence Identification (SSI)
CUNY Nonsense Syllable Test (CUNY-NST)	Central Institute for the Deaf (CID) W-22	CID Everyday Sentences
	Modified Rhyme Test (MRT)	Hearing In Noise Test (HINT)
	California Consonant Test (CCT)	Speech In Noise (SIN)

Table 2. Mean speech-perception scores for SNR, RT, and distance.

SNR	Distance in Feet	RT in Seconds			
		0.0	0.4	0.8	1.2
Quiet	6	100%	100%	98%	98%
	Average 12 and 24	100%	99%	96%	94%
+6 dB	6	81%	77%	71%	66%
	Average 12 and 24	81%	71%	61%	57%
0 dB	6	46%	41%	41%	25%
	Average 12 and 24	50%	37%	31%	22%

Adapted from Crum (1974).

Table 3. Mean percent correct $\pm$ 1 standard deviation of speech-perception scores through hearing aids for binaural listening conditions. Results of one normal subject in quiet in parentheses.

Reverberation Time (Seconds)	SNR (dB)	Normal	Hearing Impaired
0.3	Quiet	(98.0 $\pm$ 1.6)	64.9 $\pm$ 7.4
	+10	--	60.7 $\pm$ 5.2
	+5	--	57.4 $\pm$ 6.0
	0	--	49.7 $\pm$ 6.5
	-5	76.6 $\pm$ 7.9	38.2 $\pm$ 7.8
	-10	48.7 $\pm$ 10.8	--
	-15	26.0 $\pm$ 8.1	--
0.6	Quiet	(95.5 $\pm$ 3.4)	57.1 $\pm$ 6.3
	+10	--	55.2 $\pm$ 4.6
	+5	--	49.9 $\pm$ 6.6
	0	82.5 $\pm$ 5.7	42.4 $\pm$ 6.4
	-5	60.7 $\pm$ 10.7	31.6 $\pm$ 7.7
	-10	38.3 $\pm$ 11.9	--

Adapted from Nabelek and Pickett (1974a).

Table 4. Mean speech-perception scores for children with normal hearing (loudspeaker-aided) and children with hearing impairment (loudspeaker- and hearing aid-aided).

RT (seconds)	SNR (dB)	Groups		
		Normal-Hearing (Loudspeaker- Aided)	Hearing-Impaired (Loudspeaker- Aided)	Hearing-Impaired (Hearing Aid- Aided)
0.0	$+\infty$	94.5	87.5	83.0
	+12	89.2	77.8	70.0
	+6	79.7	65.7	59.5
	0	60.2	42.2	39.0
0.4	$+\infty$	92.5	79.2	74.0
	+12	82.8	69.0	60.2
	+6	71.3	54.5	52.2
	0	47.7	28.8	27.8
1.2	$+\infty$	76.5	61.8	45.0
	+12	68.8	50.2	41.2
	+6	54.2	39.5	27.0
	0	29.7	15.3	11.2

Adapted from Finitzo-Hieber and Tillman (1978).

Table 5. Mean percent correct $\pm$ 1 standard deviation of initial and final consonant speech-perception scores.

Reverberation Condition	Initial Consonant	Final Consonant
Quiet	98.80 $\pm$ 1.15	94.36 $\pm$ 3.73
Reverberant	93.36 $\pm$ 4.74	84.48 $\pm$ 5.10

Adapted from Gelfand and Silman (1979).

Table 6. Mean percent correct speech-perception scores for young normal hearing, elderly "normal" hearing, and elderly subjects with hearing impairment.

Noise Condition	RT (seconds)	Young Normal- Hearing	Elderly "Normal- Hearing"	Elderly Hearing- Impaired
Quiet	Sound Suite	96.0	96.8	84.0
	0.59	94.8	91.0	85.0
	1.56	86.6	85.0	55.2
Noise (SNR = +10 dB)	Sound Suite	91.2	90.8	74.6
	0.59	79.2	68.8	50.4
	1.56	68.8	53.8	36.4

Adapted from Harris and Reitz (1985).

Table 7. Mean consonant identification scores and standard deviations (in parentheses) for adult subjects with normal hearing.

Vowel	Initial			Final		
	Baseline	Noise	Reverberation	Baseline	Noise	Reverberation
/a/	94.9 (2.5)	69.9 (5.5)	80.6 (4.0)	90.0 (5.6)	60.8 (2.8)	69.3 (5.7)
/i/	93.1 (3.0)	60.3 (6.9)	62.6 (6.6)	91.8 (3.5)	55.4 (5.1)	70.3 (4.8)

Adapted from Nabelek and Letowski (1986).

Table 8. Mean consonant identification scores and standard deviations (in parentheses) as a function of listening condition, SL, and age group.

Group	Listening Condition							
	Control		Reverberation		Noise		Rever. + Noise	
<u>30 dB SL</u>								
Adults	63.4	(13.4)	55.4	(9.7)	58.2	(12.4)	55.4	(11.2)
14-15 years	58.9	(14.3)	47.5	(10.3)	51.4	(11.4)	46.1	(7.5)
10-11 years	57.8	(12.2)	47.2	(9.9)	50.6	(10.0)	43.1	(10.5)
6-7 years	47.5	(13.5)	39.2	(13.7)	40.7	(12.2)	35.9	(9.4)
mean	56.9	(14.7)	47.3	(12.5)	50.2	(13.2)	45.1	(11.0)
<u>40 dB SL</u>								
Adults	74.7	(10.4)	62.4	(8.2)	62.0	(10.3)	53.3	(9.7)
14-15 years	69.6	(11.2)	58.2	(9.6)	57.0	(9.7)	48.6	(8.5)
10-11 years	67.1	(11.1)	52.2	(9.0)	53.9	(10.2)	46.2	(11.3)
6-7 years	58.1	(11.7)	46.8	(8.7)	43.7	(10.2)	39.9	(8.0)
mean	67.4	(12.7)	54.9	(10.7)	54.1	(12.2)	47.0	(10.7)
<u>50 dB SL</u>								
Adults	80.5	(6.9)	62.2	(9.3)	66.0	(8.9)	58.1	(8.0)
14-15 years	75.4	(10.7)	61.0	(9.3)	59.6	(9.7)	48.6	(7.6)
10-11 years	70.3	(11.1)	55.7	(9.1)	56.8	(10.9)	46.3	(8.9)
6-7 years	61.3	(10.3)	50.3	(9.9)	46.9	(9.5)	42.9	(11.2)
mean	71.9	(12.3)	57.3	(10.6)	57.3	(11.8)	49.0	(10.7)
<u>60 dB SL</u>								
Adults	80.1	(7.9)	65.3	(8.7)	65.7	(8.2)	58.3	(7.7)
14-15 years	77.9	(7.5)	60.3	(9.9)	59.9	(9.1)	52.3	(7.8)
10-11 years	72.5	(11.4)	57.4	(10.4)	55.3	(9.4)	45.0	(9.0)
6-7 years	64.5	(10.8)	52.2	(10.5)	46.8	(10.2)	40.4	(10.4)
mean	73.7	(11.4)	58.8	(11.0)	56.9	(11.6)	49.0	(11.2)

Adapted from Johnson (2000).

Table 9. Speech-perception scores in percentage correct for vowels in conditions without and with reverberation.

Subject	Reverberation Time	
	0.0 seconds	1.2 seconds
1	84.7	81.0
2	82.7	62.3
3	87.3	75.0
4	98.7	93.0
5	94.0	91.0
6	97.3	61.7
7	92.7	71.3
8	96.7	89.3
9	68.3	58.0
10	89.7	82.3
Mean	88.6	76.5
Standard Deviation	9.5	12.9

Adapted from Nabelek and Letowski (1985).

Table 10. Mean percent correct $\pm$ 1 standard deviation of group speech-perception scores in quiet and noise for different RTs.

	RT (seconds)	Normal	Mild	Moderate-to- Severe
Quiet	Sound Suite	96.0 $\pm$ 2.8	88.0 $\pm$ 13.7	75.0 $\pm$ 14.8
	0.54	94.8 $\pm$ 2.7	82.0 $\pm$ 8.1	62.6 $\pm$ 23.5
	1.55	86.6 $\pm$ 6.7	68.2 $\pm$ 15.9	38.8 $\pm$ 14.7
Noise (+10 dB SNR)	Sound Suite	91.8 $\pm$ 5.5	77.2 $\pm$ 13.9	62.6 $\pm$ 12.5
	0.54	81.2 $\pm$ 7.7	55.6 $\pm$ 20.1	39.6 $\pm$ 14.4
	1.55	68.8 $\pm$ 11.4	53.8 $\pm$ 14.5	36.4 $\pm$ 12.1

Adapted from Harris and Swenson (1990).

Table 11. Mean speech-perception scores in percentage correct for various SNRs, RTs, and listening conditions.

RT	SNR (dB)	Unaided		Aided	
		Monaural	Binaural	Monaural	Binaural
0.1 second	Quiet	81.4	85.1	89.3	91.0
	+10	71.9	75.9	78.3	82.6
	+5	63.9	68.3	65.5	69.3
	0	41.9	52.8	42.0	53.9
	-5	19.4	28.3	18.2	28.2
0.5 second	Quiet	62.7	69.0	73.3	78.5
	+10	42.4	52.2	53.0	53.7
	+5	26.8	31.4	28.8	32.1

Adapted from Nabelek and Mason (1981).

Table 12. Mean SRT relative to the respective values at 0-degrees azimuth.

Room	Hearing Aid	Azimuth (degrees)	Mean SRT (dB)
Dead (RT=0.156 s)	Omnidirectional	45	3.1
		90	3.4
		135	2.9
		180	0.9
	Directional	45	2.8
		90	2.0
		135	-0.2
		180	-3.0
Reverberant (RT = 0.883 s)	Omnidirectional	45	0.6
		90	0.7
		135	1.1
		180	-0.4
	Directional	45	-0.1
		90	0.8
		135	-0.3
		180	-0.9

Adapted from Leeuw and Dreschler (1991).

Table 13. Speech Recognition Threshold (SRT) differences of normal-hearing listeners with hearing aids in a room with RT = 0.883 second.

	Loudspeaker-to-Subject 0.5 m		Loudspeaker-to-Subject 1.4 m	
	0-degrees azimuth noise	180-degrees azimuth noise	0-degrees azimuth noise	180-degrees azimuth noise
Mean SRT for each distance and azimuth (dB)	0.36	1.20	0.87	1.87
Mean SRT for each distance (dB)	0.78		1.37	

Adapted from Leeuw and Dreschler (1991).

Table 14. Configuration of virtual sound fields used in Gold's (1994) study.

Virtual Sound Field Number	Early Reflections			Reverberation			
	Delay (milliseconds)	Angle (degrees)	Level re direct	RT (seconds)	Pre Delay (milliseconds)	Angle (Degrees)	Level re direct
SF-1 (anechoic)	none	none	none	none	none	none	none
SF-3	20	0	-5	none	none	none	none
	30	0	-5				
	35	0	-5				
	45	0	-5				
SF-10	20	-90	-10	1.0	50	± 90	-10
	30	+90	-10				
	35	-90	-10				
	45	+90	-10				
SF-14	20	0	-10	1.0	50	± 90	-10
	30	0	-10				
	35	0	-10				
	45	0	-10				
SF-15	20	-45	-10	1.0	50	± 0	-10
	30	+45	-10				
	35	-45	-10				
	45	+45	-10				
SF-16	20	-90	-10	1.0	50	± 90	-10
	30	+90	-10				
	35	-90	-10				
	45	+90	-10				
SF-17	20	-90	-10	2.1	50	± 90	-10
	30	+90	-10				
	35	-90	-10				
	45	+90	-10				
SF-18	20	-45	-10	2.1	50	± 90	-10
	30	+45	-10				
	35	-45	-10				
	45	+45	-10				
SF-19	20	0	-10	2.1	50	± 90	-10
	30	0	-10				
	35	0	-10				
	45	0	-10				
SF-20	20	-90	-10	2.1	50	± 0	-10
	30	+90	-10				
	35	-90	-10				
	45	+90	-10				
SF-22	none	none	none	2.1	50	± 0	-10
SF-24	none	none	none	2.1	50	± 90	-10

Adapted from Gold (1994).

Table 15. Average ratings of spatial impression with 95% confidence intervals of 12 sound fields from Group 2.

Virtual Sound Field Number	Spatial Impression Mean	95% Confidence Interval
SF-1	2.4	2.0-2.8
SF-3	2.7	2.3-3.2
SF-10	3.7	3.3-4.2
SF-14	4.0	3.6-4.4
SF-15	3.8	3.4-4.1
SF-16	4.3	3.9-4.7
SF-17	5.3	5.0-5.5
SF-18	5.2	4.8-5.5
SF-19	5.0	4.6-5.2
SF-20	4.8	4.4-5.1
SF-22	3.9	3.4-4.4
SF-24	5.7	5.3-6.0

Adapted from Gold (1994).

Table 16. Number of subjects who made errors in ranking the sound fields according to width for various levels of reverberant energy.

C_{80}	Number of Subjects Who Made Errors
30.0 dB	1
9.6 dB	3
6.8 dB	4
3.9 dB	6
2.5 dB	7

Adapted from Soulodre and Bradley (1994).

Table 17. Perceived change in apparent source width as a function of the change in lateral fraction (LF) for three levels of reverberation.

C_{80} (dB)	ΔLF (1000 Hz)		
	0.05, 0.12	0.12, 0.20	0.20, 0.27
2.5	1.2	1.9	2.4
6.8	1.3	2.5	3.5
30.0	2.4	4.1	4.8

Adapted from Soulodre and Bradley (1994).

Table 18. Perceived change in listener envelopment due to a cluster of energy as a function of time and cluster level.

Gated Burst Delay (milliseconds)	70 Millisecond Gated Burst	
	@ -1 dB	@ -6 dB
0	1.0	1.2
80	1.7	3.2
≥ 100	3.2	4.0

Adapted from Soulodre and Bradley (1994).

Table 19. Mean speech-perception scores of the four subject groups for the reverberant low-predictability SPIN sentences, at four reverberation times.

Subject Group	Reverberation Time			
	0.2	0.3	0.4	0.6
Young Normal	96%	89%	85%	65%
Elderly Normal	93%	82%	72%	50%
Young HI	80%	76%	68%	50%
Elderly HI	79%	71%	56%	26%

Adapted from Gordon-Salant and Fitzgibbons (1993).

CHAPTER 3 METHODS

Participants

Twenty-two adults (18 females, 4 males) with normal-hearing sensitivity served as participants for this experiment. Participants ranged in age from 18-28 years of age, with a mean age of 20.7 years. All participants met the following criteria:

- (1) Pure-tone thresholds equal to or better than 20 dB HL at all frequencies tested (250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz);
- (2) Normal middle ear function as indicated by tympanometry;
- (3) Normal otoacoustic emissions (OAEs);
- (4) English as a primary language as reported by the participant;
- (5) Negative history of learning disability, an attentional deficit disorder, or an auditory processing disorder as reported by the participant; and
- (6) No significant medical problems as reported by the participant on the University of Florida Speech and Hearing Clinic Adult Audiologic Case History Form. A copy of this form can be found in Appendix A.

Prior to participating in the study, each participant was required to sign an Informed Consent Form approved by the University of Florida Institutional Review Board (IRB).

Speech Perception Stimuli

The Modified Rhyme Test (MRT) served as the speech stimuli for the speech-perception testing (House, Williams, Hecker, and Cryter, 1965). The MRT consists of 6 lists. Each list contains 50 sets of 6 one-syllable words. Each word is constructed in a consonant-vowel-consonant (CVC) sequence, with words in each set differing only in the

initial or final consonant sound. An example of a response set of MRT words that assess initial consonant perception is: dip, sip, hip, tip, lip, rip. An example of a response set of MRT words that assess final consonant perception is: fit, fib, fizz, fill, fig, fin. Listeners are instructed to circle the word they hear. The MRT was recorded using a carrier sentence, "Circle the _____ again." The MRT has been shown to have high test-retest reliability (House, et al., 1965). A complete list of all MRT words can be found in Appendix B. The MRT was presented via a commercially-available compact disc (CD) (© Cosmos Distributing Inc., Winnipeg, Manitoba, Canada).

Noise Competition

Speech-spectrum noise served as the noise competition in the actual rooms. The speech-spectrum noise consisted of equal energy per frequency from 125 to 1000 Hz with a 12-dB-per-octave roll-off from 1000 to 6000 Hz (Grason-Stadler Inc., 1995). The speech-spectrum noise was produced by a Grason-Stadler Instruments (GSI) Model 61 (GSI-61) clinical audiometer and recorded onto a CD.

Reverberation Simulations

Two simulations of reverberation, one software-based and one hardware-based, were examined. The CATT-Acoustic program is an impulse-response based acoustic measurement and simulation tool. The program allows one to develop a room design three dimensionally, to assign absorption and scattering coefficients to the surfaces, and to locate listeners and sound sources in the room. In addition, the CATT-Acoustic program can propagate sounds from a variety of natural and amplified sources and calculate binaural impulse responses. The binaural impulse responses can be used to calculate a variety of acoustical measurements and to produce auralizations. These are

aural simulations based on detailed calculations of thousands of sound rays arriving at each of the listeners' ears that are convolved or mixed with anechoic music or speech so one can aurally simulate the acoustical qualities of the rooms.

A second simulation was made using the Lexicon MPX-550 Effects Processor. The Lexicon MPX-550 is a stereo, hardware dual channel processor. The two channels can control different effects independently. For example, one channel may control the characteristics of reverberation while the other channel controls delay, modulation, or pitch algorithms. The RT may be adjusted from 0.5 second to infinity using 0.1-second increments. The delay time can range from 0 to 930 ms, and can be adjusted in 20-millisecond increments. The delayed signal may be filtered with a variable high cut (full pass to 320 Hz) and low cut (full pass to 1350 Hz). Additionally, the sound can be routed through a one-third octave graphic equalizer to simulate sound reflections or absorptions at particular frequencies for a given room surface more closely. The Lexicon MPX-550 has 240 pre-programmed settings with reverberation algorithms such as room, chamber, plate, gate, hall, and ambiance. In addition, the Lexicon MPX-550 is capable of storing up to 64 user programs. Each program can contain up to eight (four program and four compression) adjustable parameters. With the Lexicon MPX-550, reverberation can be combined with delay, modulation, and pitch effects.

Procedures

Twenty-two volunteers met the inclusion criteria as stated above and were included as participants. Two of the original 24 volunteers were not included as participants because one had a previous major medical condition and the other did not have normal OAEs. Recall that the original research proposal called for 20 participants

to be tested. Individuals who met the other inclusion criteria to be participants had their hearing sensitivity tested. The pure-tone air conduction test consisted of octave intervals from 250-8000 Hz, as well as 3000 and 6000 Hz. Hearing sensitivity was tested in a sound-treated booth using a GSI-61 clinical audiometer and TDH-50P headphones following the American Speech-Language-Hearing Association (1978) guidelines. Participants were required to have thresholds better than or equal to 20 dB HL at all frequencies tested in both ears in order to participate in the study. Figure 1 shows an audiogram of the mean thresholds for the 22 participants. Tympanograms were obtained via a GSI-33 Middle Ear Analyzer. Participants were required to have middle-ear pressure between -100 to +100 decaPascals (daPa), compliance of 0.2 to 2.5 cubic centimeters (cm^3) and ear-canal volume of 0.5 to 2.0 cm^3 , in both ears. Participants had otoacoustic emissions (OAE) testing using a Welsh Allyn GSI-60 DPOAE System. The GSI-60 was configured using the Diagnostic 65/55 stimulus and the Diagnostic configuration. Normal range was defined as otoacoustic emissions above the lower limit of normal range of the Vanderbilt 65/55 protocol (Table 20) on the GSI-60.

The speech-perception abilities of participants were tested in each of the three actual rooms that had different dimensions and RTs. Room dimensions (width x length x height, in meters) were: 4.6 x 9.1 x 2.4 for the short-RT room, 4.6 x 5.8 x 2.7 for the medium-RT room, and 6.1 x 12.2 x 6.1 for the long-RT room. Reverberation times were approximately 0.5, 1.3 and 5.3 seconds, averaged over 500, 1000 and 2000 Hz, for the short-RT, medium-RT, and long-RT rooms, respectively. The RTs in this study were representative of different everyday listening environments, such as classrooms and auditoriums. Reverberation times measured at octave band frequencies are shown in

Table 21. In order to achieve these measurements, an IVIE Technologies, Inc. IE-84 pink noise generator, a Crown Macro-Tech 2400 amplifier, and a JBL MR Series loudspeaker were utilized to generate pink noise at a level above 100 dB SPL. The IVIE PC40 real-time analyzer then was used to measure the RT at 125, 250, 500, 1000, 2000, 3000, 4000, and 8000 Hz. The microphone was mounted on a stand 44 inches above the floor for all measurements. This height approximated the ear level of a seated adult. Four to six measurements of RT were taken at different locations within the unoccupied room. All RT measurements were made with the IVIE PC-40 microphone beyond the critical distance of the room. Critical distance is defined as the distance (measured in meters from the sound source) at which direct sound and the reverberant sound are equal in intensity. Critical distance can be described by the formula:

$$Dc = (0.20) \sqrt{\frac{VQ}{nRT}}$$

where V = volume of the room in cubic meters, Q = directivity of the source, n = number of sources, and RT = room reverberation time (RT₆₀) at 1400 Hz (Klein, 1971; Peutz, 1971).

Participants listened to one 50-word MRT list per listening condition. The order of all MRT lists was randomized. Seating charts of participants in the 0.5-, 1.3-, and 5.3-seconds RT actual rooms are shown in Figures 2 through 4, respectively. In the actual rooms, all participants were seated beyond the critical distance of the room. Participants were tested in conditions without added noise and with added noise. The noise competition utilized speech-spectrum noise produced by a GSI-61 clinical audiometer and recorded onto a CD. Ideally, participants would have been tested in all conditions without noise; however, pilot data suggested there was a ceiling effect for speech-

recognition scores in rooms with shorter RTs. Therefore, participants were tested in each room in conditions without added noise and with added noise (SNR = 0 or -10 dB). The SNR of -10 dB was determined, via pilot study data, as the SNR necessary to eliminate ceiling effects for the rooms with shorter RTs (0.5 and 1.3 seconds). The SNR of 0 dB for the room with the longer RT (5.3 seconds) was chosen to eliminate floor effects that were present with a SNR of -10 dB. For conditions with SNR = 0 or -10 dB in the actual rooms, the noise was introduced into the sound field via 4 loudspeakers placed 1 meter from, and facing, each corner of the room. The speaker arrangements for each room are shown in Figures 2 through 4. Sound levels were calibrated in dBA using an IVIE PC-40 measurement system. Speech stimuli were measured with the microphone placed 1 meter from the loudspeaker and calibrated to 65 dBA at 1 meter. Recordings of the samples of the speech stimuli were measured only when the stimuli was present (i.e., the pauses between sentences were not sampled). The noise stimuli were calibrated with the microphone located in the center of the room. For all conditions with noise added (SNR = 0 or -10 dB), the speech-spectrum noise was played before the MRT list begins, and was continuous until after the MRT list is completed. For the simulations, the speech-spectrum and ambient noise was modified to closely match the noise spectra in the actual room. Ambient noise levels were 35.3, 42.6, and 50.7 dBA for the short-RT, medium-RT, and long-RT rooms, respectively. The ambient noise level of the long-RT room was comparatively high due to air-conditioner noise that could not be turned off during the testing. Noise levels were measured via the IVIE PC-40, with the microphone located in the center of the participants' seating area.

All participants were tested in the actual rooms. The order testing was contingent upon the availability of the rooms. The actual room testing order was long RT, medium RT, and short RT. In each room, the condition of added noise was presented before the condition of no added noise in order to limit potential learning effects on the MRT. All actual room testing was completed prior to testing with the simulated reverberation conditions.

For all simulated reverberation conditions, participants were tested in a sound-treated booth. The computer simulation using CATT-Acoustic was constructed by Hyeongseok Kim using the following procedure:

- (1) Acoustical measurements were made in the actual rooms (as described above). In addition to acoustical measurements, physical measurements of the room were made, and pictures were taken of, notes were made about, and/or blueprints were consulted regarding the furnishing materials in each room. For more information regarding the measurement of RT of rooms, the reader is referred to the International Organization for Standardization ISO3382 (1997).
- (2) The room and furnishings were modeled into AutoCAD and imported into the CATT-Acoustic program. This step involved drawing (via computer) the physical dimensions of the room and furnishings (e.g., desks, chairs and light fixtures). Text files were created that contained the absorption and diffusion coefficients of the materials (e.g., ceiling, wall, and floor surfaces, desk and chair materials, people, etc.). The completed AutoCAD model was then imported into the CATT-Acoustic program.
- (3) The sound source was configured to approximate a human speaker. In the CATT-Acoustic program, the position, directivity and sound pressure levels of the speaker were assigned as if the speaker were centered at the front of the classroom speaking at a level of 65 dBA measured 1 meter from the mouth. The receiver positions were the same positions in which the acoustical measurements were made with the IVIE.
- (4) Estimated diffusion coefficients and absorption coefficients were obtained from standard sources. Absorption coefficients were attained from manufacturer data or from standard source such as Egan (1987). Diffusion coefficients were calculated at 20% for the CATT-Acoustic program because no standard data is available such coefficients.

The hardware simulation via the Lexicon MPX-550 was constructed in the following manner:

- (1) Sample recordings of the short-RT and medium-RT rooms were sent to a representative of Lexicon, Incorporated via electronic mail.
- (2) An A/B procedure was followed by Lexicon in order to attempt to simulate the conditions within the actual rooms. An A/B procedure is a listening comparison between the source material and the simulation. The evaluator listens to the source material and then to the simulation. The simulation then is adjusted to match the source material more closely.
- (3) Lexicon sent suggested settings for the short-RT and medium-RT rooms to the investigator, as well as a suggested preset for the long-RT room via electronic mail (Scott Pizzo, personal communication, February 25, 2003).
- (4) The settings for the long-RT room were calculated via the MPX-550 instruction manual to meet the RT requirements of the actual room. An A/B comparison was conducted for the long-RT room as well.
- (5) The Lexicon MPX-550 was pre-set to simulate each actual room (see Table 22 for settings). A listening check was conducted at each RT to verify the closeness of the actual and simulated reverberation listening conditions.
- (6) The MRT CD was played on a Sony CDP-CE375 CD player, routed through the Lexicon MPX-550, a Peavey Q431F equalizer, a Crown D-75A amplifier and out the loudspeakers in the IAC booth. Measurements of the speech spectra were taken with the IVIE PC-40.
- (7) The resulting spectra then were compared to the spectra recorded in the actual rooms until they closely approximated the actual room spectra. Recall that the actual room speech spectra included both speech and ambient room noise. The effect of the ambient noise on the measurement of the speech spectra was demonstrated by overlaying the speech spectra from the actual rooms (which included ambient noise) with the ambient noise spectra from the actual rooms. An example of such a procedure is shown in Figure 5. Generally, the ambient room noise was most intense below 125 Hz for all actual rooms. Due to the low-frequency energy of the ambient noise in the actual rooms, the Lexicon MPX-550 speech spectra were matched to the actual room measurements at and above 125 Hz. This procedure was followed because otherwise the speech spectra for the simulations may have had more low-frequency emphasis than the speech spectra that were presented in the actual rooms. The noise spectra for the simulations were matched with the noise spectra from the actual room environments in a separate procedure (detailed below) so that the noise stimuli could be presented separately from the speech stimuli. A goal of actual room measurements ± 1 dB was used for frequencies at or above 125 Hz. The differences

in the means of the spectra (actual to Lexicon MPX-550) averaged from 125 to 16000 Hz were 0.25 dB for the short RT, 0.75 dB for the medium RT, and -0.625 dB for the long RT.

- (8) The MRT was played on a Sony CDP-CE375 CD player, routed through the Lexicon MPX-550 and equalizer, and recorded onto CD via a Pioneer PDR-509 CD recorder. The recorded spectra were compared again to the actual room spectra.

The CATT-Acoustic and Lexicon MPX-550 simulated reverberation conditions were pre-recorded on a CD and presented via a CD player through a GSI-61 clinical audiometer through a Tannoy System 600 loudspeaker located at 0-degrees azimuth. This loudspeaker closely approximated the directional characteristics of the human voice ($Q = 2.5$). For conditions with added noise ($SNR = 0$ or -10 dB), the noise competition was modified speech-spectrum noise recorded onto a CD and introduced into the sound field via four Definitive Technology BP-2X loudspeakers located at 45, 135, 225, and 315 degrees azimuth. Recall that noise spectra are altered by the acoustical characteristics of each room. Specifically, each room has background noise and reverberation. When a signal, such as speech-spectrum noise, is added to the room, the resulting spectrum is a combination of the spectrum of the signal, the background noise spectrum of the room, and the effects of reverberation on the noise. Therefore, it was necessary to modify the speech-spectrum noise to approximate more closely the noise with room effects. The ambient noise (for the quiet conditions) and the noise competition (for the noise conditions) were created as follows:

- (1) Speech-spectrum noise from the GSI-61 audiometer was routed through a Peavey Q431F one-third octave band graphic equalizer in order to flatten the spectrum, and recorded on a Sony DTC-690 digital audio tape (DAT) recorder.
- (2) The DAT recording of the noise was routed a second time through the equalizer, to flatten the spectrum further, and recorded on a Pioneer PDR-509 CD recorder.

- (3) The CD that contained the speech-spectrum noise was played on a Sony CDP-CE375 CD player, routed through the Peavey Q431F equalizer, a Crown D-75A amplifier, and to the Definitive Technology BP-2X loudspeakers in the sound booth. The spectra were measured using the IVIE PC-40, with the microphone located 1 m from the loudspeaker.
- (4) The resulting spectra were then compared to the spectra recorded in the actual rooms and modified until they closely approximated the actual room spectra.
- (5) The noise was recorded onto a CD. The recorded noise spectra were compared again to the actual room spectra. Noise spectra for the actual room and simulated conditions can be found in Appendix C.

All simulated reverberation conditions were randomized. The participants listened to one 50-word MRT list for each simulated reverberation condition in quiet and noise. For each simulated RT, conditions with added noise were presented before conditions without added noise, to reduce any learning effects on the MRT. All MRT lists also were randomized.

In summary, participants were tested in the following conditions:

- (1) Actual Room #1, without added noise ($RT \cong 0.5$ -second);
- (2) CATT-Acoustic simulation of Actual Room #1 without added noise ($RT \cong 0.5$ -second);
- (3) Lexicon MPX-550 simulation of Actual Room #1 without added noise ($RT \cong 0.5$ -second);
- (4) Actual Room #1, with added noise ($RT \cong 0.5$ -second, $SNR = -10$ dB);
- (5) CATT-Acoustic simulation of Actual Room #1 with added noise ($RT \cong 0.5$ -second, $SNR = -10$ dB);
- (6) Lexicon MPX-550 simulation of Actual Room #1 with added noise ($RT \cong 0.5$ -second, $SNR = -10$ dB);
- (7) Actual Room #2, without added noise ($RT \cong 1.3$ seconds);
- (8) CATT-Acoustic simulation of Actual Room #2 without added noise ($RT \cong 1.3$ seconds);

- (9) Lexicon MPX-550 simulation of Actual Room #2 without added noise (RT $\cong$ 1.3 seconds);
- (10) Actual Room #2, with added noise (RT $\cong$ 1.3 seconds, SNR = -10 dB);
- (11) CATT-Acoustic simulation of Actual Room #2 with added noise (RT $\cong$ 1.3 seconds, SNR = -10 dB);
- (12) Lexicon MPX-550 simulation of Actual Room #2 with added noise (RT $\cong$ 1.3 seconds, SNR = -10 dB);
- (13) Actual Room #3, without added noise (RT $\cong$ 5.3 seconds);
- (14) CATT-Acoustic simulation of Actual Room #3 without added noise (RT $\cong$ 5.3 seconds);
- (15) Lexicon MPX-550 simulation of Actual Room #3 without added noise (RT $\cong$ 5.3 seconds);
- (16) Actual Room #3, with added noise (RT $\cong$ 5.3 seconds, SNR = 0 dB);
- (17) CATT-Acoustic simulation of Actual Room #3 with added noise (RT $\cong$ 5.3 seconds, SNR = 0 dB);
- (18) Lexicon MPX-550 simulation of Actual Room #3 with added noise (RT $\cong$ 5.3 seconds, SNR = 0 dB).

Statistical Analyses

The dependent variable, speech-perception scores on the MRT, was analyzed using a four-way repeated measures analysis of variance (ANOVA) procedure. The speech-perception data analyses were completed for initial and final consonant confusions, comparing each actual room to the two simulations of that room. Scores for total percent correct were not included in the statistical analyses because the total percent correct score is a direct function (mean) of the initial and final consonant percent correct scores. Including the mean of the two levels in the statistical analyses would decrease variation within the consonant position factor, thereby obscuring any true difference in speech-perception scores. All analyses were tested at $\alpha = 0.05$.

Table 20. Normal range of OAEs per the Vanderbilt 65/55 protocol on the GSI-60 DPOAE system.

Frequency	Lower OAE	Upper OAE	Noise Upper
562	-6	11	-6
625	-4	12	
687	-3	14	-8
781	-3	16	
875	-2	16	
968	-1	19	
1093	-3	18	-8
1250	-1	17	
1375	-4	16	
1562	-2	15	-9
1750	-3	14	
1968	-4	11	-11
2218	-6	11	
2500	-5	13	
2781	-4	8	
3093	-3	10	-11
3500	-2	10	
3937	-4	12	-10
4406	-5	12	
4968	-5	10	
5562	-11	9	
6250	-14	4	-10

Table 21. Reverberation times (RTs) in seconds by octave for the three actual rooms.
Average RT is the mean RT of 500, 1000, and 2000 Hz.

Room RT	Frequency (Hz)							Ave.
	125	250	500	1000	2000	4000	8000	
Short	0.8	0.8	0.6	0.5	0.5	0.5	0.5	0.53
Medium	1.4	1.2	1.2	1.4	1.4	1.2	1.1	1.33
Long	2.9	4.7	5.2	5.2	5.4	3.7	2.4	5.27

Table 22. Lexicon MPX-550 settings for simulation of actual room RTs.

	Room					
	Short RT		Medium RT		Long RT	
Preset	#20 Small Hall		#43 Midsize Ambience		#22 Large Hall	
Settings	MidRT	79	HC	57	MidRT	75
	Decay	1.36 s	Size	26.0	Decay	2.50 s
	HFrolloff	2.1 kHz	HFrolloff	2.5kHz	HFrolloff	4.5 kHz
	Mix	40%	Mix	41%	Mix	85%
	PreDelay	0ms	Level	100	PreDelay	0ms
	Bass Mult	.8x	PreDelay	0ms	Bass Mult	1.5x
	Bass Xovr	367 Hz	Decay	225ms	Bass Xovr	252 Hz
	RtHC	3.3 kHz	Rvblvl	-30 dB	RtHC	10.3 kHz
	Diff	70	RtHC	4.0kHz	Diff	48
	Size	23.5m	Diff	35%	Size	50.0m
	Attack	140ms	Level	100%	Attack	120ms
	Level	100%	CmpRatio	1:1 (off)	Level	100%
	EkoDlyL	0ms	Threshold	-20 dB	EkoDlyL	0ms
	EkoDlyR	0ms	CmpAttk	8ms	EkoDlyR	0ms
	EkoFbkL	0%	CmpRels	30ms	EkoFbkL	0%
	EkoFbkR	0%			EkoFbkR	0%
	CmpRatio	1:1 (off)			CmpRatio	1:1 (off)
	Threshold	-20 dB			Threshold	-20 dB
	CmpAttk	8ms			CmpAttk	8ms
	CmpRels	30ms			CmpRels	30ms

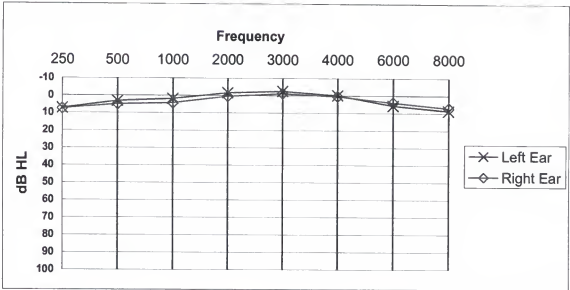


Figure 1. Mean pure-tone air conduction data for the 22 participants.

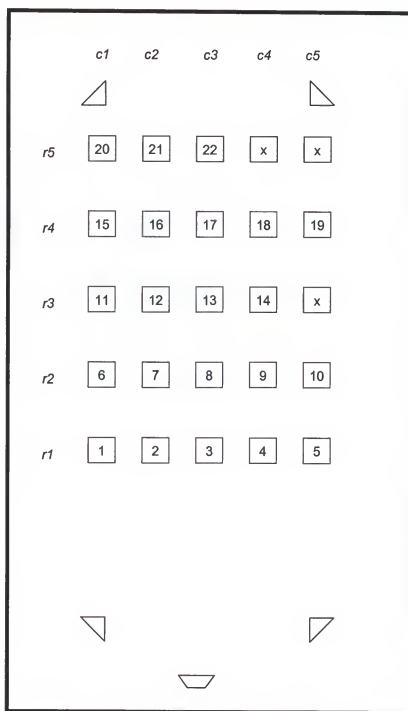


Figure 2. Seating arrangement and speaker positions for participants in the short-RT room (drawing not to scale). () = noise speaker; () = speech speaker; c1 = column number; r1 = row number; () = participant number; (x) = no participant seated.

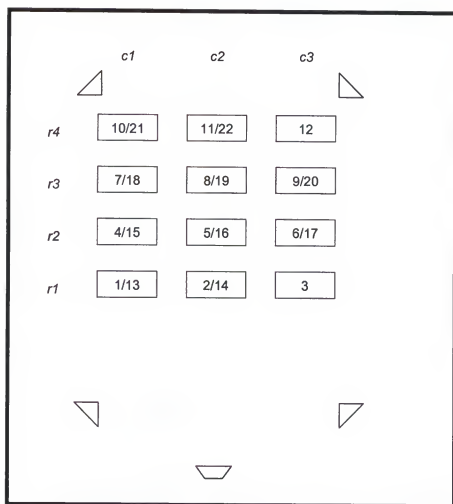


Figure 3. Seating arrangement and speaker positions for participants in the medium-RT room (drawing not to scale). ($\triangle$) = noise speaker; (∇) = speech speaker; c1 = column number; r1 = row number; ($\frac{1}{1}$) = participant number.

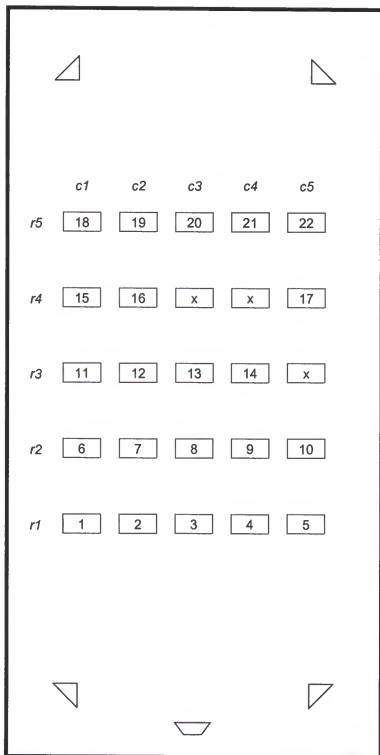


Figure 4. Seating arrangement and speaker positions for participants in the long-RT room (drawing not to scale). () = noise speaker, () = speech speaker; c1 = column number; r1 = row number; () = participant number; (x) = no participant seated.

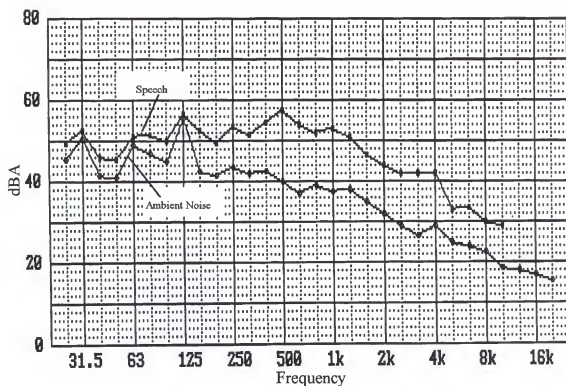


Figure 5. Comparison of the speech spectrum and the ambient noise spectrum for the long-RT actual room.

CHAPTER 4

RESULTS

The statistical analysis conducted was a four-factor repeated measures analysis of variance (ANOVA). This type of ANOVA has an $A \times B \times C \times D$ design and may be utilized because all participants completed testing in all conditions (Agresti and Finlay, 1997). The four factors were room environment (actual room, CATT-Acoustic simulation, Lexicon MPX-550 simulation), reverberation (0.5, 1.3, 5.3 seconds), noise competition (added, no added), and position (initial consonant and final consonant percent correct). The source table for the ANOVA, which lists higher-order interactions as well as main effects, is presented in Table 24. For an ANOVA, if the four-factor interaction ($A \times B \times C \times D$) is statistically significant, the three-factor interactions ($A \times B \times C$; $A \times B \times D$; $A \times C \times D$; and $B \times C \times D$) are evaluated (Agresti and Finlay, 1997; Gravetter and Wallnau, 2000). If the p -value is small (i.e., $p < \alpha$) for the three way interactions, pairwise comparisons (two-factor interactions) are made. For example, if the three-factor interaction $A \times B \times C$ has a small p -value, the two-factor interactions ($A \times B$; $A \times C$; $B \times C$) are examined. If there are only two levels of a factor in the ANOVA and there is statistical significance between the two levels, no further post-hoc tests are necessary. If a factor with more than two levels is involved in a significant interaction, the post-hoc analysis involves examining means from the levels of one factor separately at each level of the other factor. For example if $B \times C$ is the only significant interaction, pairwise comparisons would be made for every level of B for each level of C . However, if one of the factors

does not have an interaction (in the above example, factor A), the main effect for the factor is tested and pairwise comparisons can be made for various means within the factor (Agresti and Finlay, 1997; Gravetter and Wallnau, 2000).

For the purposes of analyzing the data, all interactions and main effects within the ANOVA will be discussed in order to examine trends more thoroughly. Analyses of lower-order interactions were conducted by plotting 95% confidence intervals. This enabled trends to be discovered while avoiding the statistical difficulties of artificially inflating the alpha level by calculating a myriad of three- and two-factor ANOVAs (Agresti and Finlay, 1997; Gravetter and Wallnau, 2000). Post-hoc analyses of main effects were conducted via Tukey's Highly Significant Difference (HSD) test. The Tukey's HSD is considered a fairly conservative multiple comparison procedure. In other words, there is less likelihood of committing a Type I error (i.e., finding significance where none exists).

The four-way interaction of room environment by reverberation by noise competition by consonant position was statistically significant at the $p < .001$ level. In other words, initial and/or final consonant speech perception varied as a function of short and/or medium and/or long RT or room environment or quiet and/or noise. Because all four factors are involved in the significant interaction, the lower-order interactions must be examined (Agresti and Finlay, 1997; Gravetter and Wallnau, 2000). The remainder of this section will examine the trends of the interactions and main effects for room environment, reverberation, noise competition, and consonant position separately. Due to the large amount of data analyses, some discussion will be provided in the results section.

Room Environment

Room Environment Main Effect

The main effect of room environment was significant ($p < .001$). Stated differently, there was a significant difference between the actual room and/or the CATT-Acoustic simulation and/or the Lexicon MPX-550 simulation. Table 25 displays the post-hoc analysis that was conducted using the Tukey's HSD multiple comparison procedure. The results demonstrated that there was not a significant difference between the actual room conditions and the CATT-Acoustic simulations ($p = .281$). However, significant differences were found between the actual room and the Lexicon MPX-550 simulation ($p < .001$) and between the CATT-Acoustic simulation and the Lexicon MPX-550 simulation ($p < .001$). These results suggest that the CATT-Acoustic simulations could approximate speech perception in actual room settings. Conversely, the Lexicon MPX-550 simulations did not approximate speech perception in the actual room settings. The significant difference between the CATT-Acoustic simulation and the Lexicon MPX-550 simulation suggests that the two simulations were not associated with similar speech-perception scores in the individuals with normal hearing.

Room Environment x Noise Competition

The room environment by noise competition interaction also was significant ($p < .001$). These results suggest significant differences for at least one of the three room environments in quiet and/or noise conditions. Analyses for this interaction were conducted by plotting 95% confidence intervals. The plots, shown in Figure 6, indicated a trend that speech perception with no added noise was significantly better than speech perception with added noise for all three room environments. Overall, these analyses

indicated that speech perception decreased with added background noise. This finding is consistent with data from numerous studies (Fletcher, 1929; Kryter, 1946; Hawkins and Stevens, 1950; Licklider and Miller, 1951; Miller and Nicely, 1955; Pickett, 1957; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Heiber and Tillman, 1978; Nabelek and Mason, 1981; Harris and Reitz, 1985; Harris and Swenson, 1990; Johnson, 2000).

Room Environment x Reverberation

The room environment by reverberation interaction was significant ($p < .001$). This significant interaction suggests the speech-perception scores in one or more of the room environments varied significantly across one or more of the RTs. To determine trends within this interaction, analyses again were conducted by examining 95% confidence intervals. Results, displayed in Figure 7, suggested a trend that as reverberation increased from 0.5 to 1.3 seconds, speech-perception scores decreased significantly for the actual room and CATT-Acoustic conditions; however, speech-perception scores did not decrease significantly for the Lexicon MPX-550 simulation. As RT increased from 1.3 to 5.3 seconds, speech-perception scores significantly decreased for the Lexicon MPX-550 simulation and for the CATT-Acoustic simulation. Somewhat surprisingly, the 1.3-seconds RT actual room had the lowest speech-perception scores for the actual rooms. Previous literature suggested that speech perception generally decreases as reverberation increases (Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Heiber and Tillman, 1978; Nabelek and Robinette, 1978; Gelfand and Silman, 1979; Nabelek and Mason, 1981; Harris and Reitz, 1985; Nabelek and Letowski, 1986; Harris and Swenson, 1990; Leeuw and Dreschler, 1991; Johnson, 2000). This finding will be addressed in greater detail in the Discussion section.

Room Environment x Consonant Position

The room environment by consonant position interaction was significant ($p < .001$). This interaction suggests that in one or more of the room environments there was a difference between initial and/or final consonant speech-perception scores. Analyses using 95% confidence intervals again were conducted to determine trends in this interaction. Results (Figure 8) delineated a trend that speech perception was better for initial consonants than for final consonants across all room environments. The differences between initial and final consonant speech-perception scores for the actual rooms did not appear to be as large as for either simulation. The reason for this difference may be explained by the different methods in which the noise was presented in the actual room versus the simulations. When the noise was introduced into the actual rooms, it was affected by the reverberation. Stated differently, the noise became “reverberant noise”. This detail was important because of a synergistic effect of noise and reverberation on speech perception (Nabelek and Nabelek, 1994; Siebein et al., 1997). In other words, noise and reverberation presented together have a more deleterious effect on speech perception than either noise or reverberation presented alone. In contrast to the noise in the actual room environment, the noise for the simulations was essentially non-reverberant because it was not modified by the simulation hardware/software. The general trend for initial consonant speech perception being better than final consonant speech perception is consistent with previous findings (Gelfand and Silman, 1979, Nabelek and Letowski, 1986).

Room Environment x Noise Competition x Reverberation

The three-factor interaction of room environment, noise competition, and reverberation also was significant ($p < .001$). Stated otherwise, speech-perception scores for one or more of the room environments varied significantly across noise and/or quiet across one or more of the RTs. The 95% confidence intervals are presented in Figure 9. Several trends may be noted. First, as noise was added (i.e., SNR decreased), speech-perception scores decreased across room environment and RT. Second, as reverberation increased, speech-perception scores generally decreased across room environment and noise competition, with the main exception being the change from the medium-RT to long-RT actual room as discussed previously. Lastly, by comparing the speech-perception scores between room environments, in most cases, the CATT-Acoustic simulations more closely approximated the actual rooms than did the Lexicon MPX-550 simulations.

Room Environment x Reverberation x Consonant Position

The three-factor interaction of room environment, reverberation, and consonant position also was significant ($p < .001$). This interaction indicates that initial and/or final consonant speech perception varied as a function RT and/or room environment. The 95% confidence intervals are presented in Figure 10. One trend from these analyses suggests that for all RTs and room environments the mean initial consonant speech-perception scores were higher (85.4%) than the mean final consonant speech-perception scores (79.7%). A second trend suggests that differences between the initial and final consonant speech-perception scores were greater for the simulations as RT increases, but remained approximately the same for the actual rooms. Recall that this interaction is collapsed

across noise conditions. This trend also may have occurred due to the differences in the noise competition between the actual rooms and the simulations as previously discussed under the room environment by consonant position interaction.

Room Environment x Noise Competition x Consonant Position

This interaction was not significant ($p = .725$). Initial and final consonant speech perception did not vary as a function of noise competition and room environment. The 95% confidence intervals are shown in Figure 11. This may be evaluated by examining the two-way interactions. As previously stated, the two-way interactions of room environment and noise competition as well as room environment and consonant position were significant. Thus, the lack of significance for this three-way interaction might be explained by the two-factor interaction of noise competition and consonant position (discussed below), which was not significant, because the speech-spectrum noise competition did not affect speech perception of initial and final consonants differently. Recall that the speech-spectrum noise was presented at a constant intensity. Thus both the initial and final consonants would be heard at the same SNR.

Noise Competition

Noise Competition Main Effect

The main effect of noise competition was significant ($p < .001$). Because there are only two levels of this factor no further post-hoc tests are necessary. Rather, one can conclude that the performance was better under the factor level with the greater mean (Agresti and Finlay, 1997). Figure 12 shows the results of this analysis. These data indicate that speech-perception scores were higher in quiet (mean = 89.8%) than in added noise (mean = 75.3%). The superiority of speech perception in the quiet condition was

obtained under all listening conditions. The well-recognized masking effect of noise on speech was the primary reason that speech-perception scores were lower when noise was added.

Noise Competition x Reverberation

The interaction of noise competition and reverberation was significant ($p < .001$). Speech perception in the quiet and/or noise conditions varied significantly across one or more of the RTs. The 95% confidence intervals for this interaction are displayed in Figure 13. Results of these analyses indicated a general trend that speech perception decreased significantly in quiet and in noise up to 1.3-seconds RT as reverberation increased. Recall that the SNR was -10 dB for the 0.5- and 1.3-seconds RTs; however, the SNR was 0 dB for the 5.3-seconds RT. The trend for the noise conditions may have been as significant as for the quiet conditions across RTs if the SNR was held constant over all RTs. Recall that the SNRs were not held constant due to the floor effects of presenting the stimuli in the long-RT room at -10 dB SNR.

Noise Competition x Consonant Position

The interaction of noise competition and consonant position was not significant ($p = .096$). Stated otherwise, initial and final consonant speech perception did not vary as a function of quiet or noise. The 95% confidence intervals for this interaction are shown in Figure 14. The addition of noise lowered both the initial and final consonant speech perception by approximately the same amount (15.7% and 13.4%, respectively). In other words, both initial and final consonants were masked by the speech-spectrum noise. The scores for the initial consonants were lowered by the noise, while the scores for the final consonants were lowered by the noise and the upward spread of masking from the vowel

(as previously discussed). For this reason, the relative difference between the initial and final consonant speech perception remained about the same. These data suggest that the addition of noise into an environment did not contribute to the difference between the initial and final consonant speech perception. Other factors (i.e., reverberation) are responsible for this difference. This effect of noise and reverberation on speech perception is consistent with previous literature (Crum, 1974; Nabelek and Pickett, 1974a, b; Harris and Reitz, 1985; Harris and Swenson, 1990; Johnson, 2000).

Noise Competition x Reverberation x Consonant Position

The three-factor interaction of competition and reverberation and consonant position was not significant ($p = .193$). There was no relative difference between initial or final consonant speech-perception scores in the various RTs when noise was added. The 95% confidence intervals for this interaction are shown in Figure 15. As previously discussed, the interaction of noise competition and reverberation was significant. However, the interaction of noise competition and consonant position was not significant. In addition, the interaction of reverberation and consonant position was significant, which suggests that there was a difference in initial and/or final consonant speech-perception scores in quiet across RTs (see below for a discussion of the two-factor interaction of reverberation and consonant position). The non-significance of this three-factor interaction suggests that noise was influencing speech perception, by reducing both initial and final consonant perception equally. This effect will be explained further in the discussion section.

Reverberation

Reverberation Main Effect

The main effect of reverberation was significant ($p < .001$). This finding suggests that speech perception was different between short RT and/or medium RT and/or long RT. Table 26 displays the post-hoc analysis that was conducted using the Tukey's HSD multiple comparison procedure. The results demonstrated that the short, medium, and long RTs were all significantly different (collapsed across all room environments, noise competitions, and consonant positions) at a $p < .001$ significance level. The trend indicated that speech perception decreases as reverberation increases. This trend is consistent with previous studies (Moncur and Dirks, 1967; Niemoeller, 1968; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Gelfand and Silman, 1979; Harris and Reitz, 1985; Nabelek and Letowski, 1986; Olsen, 1988; Harris and Swenson, 1990; Leeuw and Dreschler, 1991; Johnson, 2000).

Reverberation x Consonant Position

The interaction of reverberation and consonant position was significant ($p < .001$). In other words, initial and/or final consonant speech perception varied as a function of short RT and/or medium RT and/or long RT. The 95% confidence intervals, shown in Figure 16, indicate a trend that the final consonant speech perception decreases more than the initial consonant speech perception as reverberation increases. The increase in RT from 0.5 to 5.3 seconds resulted in a decrease of 11.3% of speech perception of initial consonants, whereas the same increase in RT resulted in a decrease of 17.9% of final consonant speech perception. This trend also is consistent with previous research (Gelfand and Silman, 1979; Nabelek and Letowski, 1986).

Consonant Position

Consonant Position Main Effect

The main effect of consonant position was significant ($p < .001$). There was a significant difference between initial and final consonant speech perception. Specifically, initial consonant speech perception was better than final consonant speech perception (collapsed across all other conditions). Figure 17 shows the means for speech perception of the initial consonant ($\mu = 85.4\%$) and final consonant ($\mu = 79.7\%$) positions. This trend is consistent with previous findings (Gelfand and Silman, 1979; Nabelek and Letowski, 1986).

Summary

To review, all four main effects (room environment, noise competition, reverberation, and consonant position) were significant at the $p < .001$ level. In addition, all interactions were significant ($p < .001$) except for the two-factor interaction of noise competition and consonant position ($p = .096$), the three-factor interaction of room environment, noise competition, and consonant position ($p = .725$), and the three-factor interaction of reverberation, noise competition, and consonant position ($p = .193$).

Table 23. Descriptive statistics for room environment, noise competition, reverberation, and consonant position factors.

Room Environment	Noise Competition	RT	Position	Mean	Standard Deviation	N
Actual	Noise	Long	Final	73.45	10.29	22
			Initial	79.55	12.47	22
			Total	76.50	11.71	44
		Medium	Final	55.45	12.36	22
			Initial	50.36	8.25	22
			Total	52.91	10.70	44
		Short	Final	71.00	15.88	22
			Initial	70.00	12.51	22
			Total	70.50	14.14	44
		Total	Final	66.64	15.15	66
			Initial	66.64	16.51	66
			Total	66.64	15.79	132
	Quiet	Long	Final	90.55	8.05	22
			Initial	84.55	9.66	22
			Total	87.55	9.30	44
		Medium	Final	85.09	4.81	22
			Initial	97.27	2.59	22
			Total	91.18	7.25	44
		Short	Final	93.64	4.88	22
			Initial	98.55	2.32	22
			Total	96.09	4.52	44
		Total	Final	89.76	6.99	66
			Initial	93.45	8.64	66
			Total	91.61	8.04	132
	Total	Long	Final	82.00	12.58	44
			Initial	82.05	11.31	44
			Total	82.02	11.89	88
		Medium	Final	70.27	17.62	44
			Initial	73.82	24.48	44
			Total	72.05	21.28	88
		Short	Final	82.32	16.30	44
			Initial	84.27	16.96	44
			Total	83.30	16.57	88
		Total	Final	78.20	16.52	132
			Initial	80.05	18.80	132
			Total	79.12	17.69	264

Table 23. Continued.

Room Environment	Noise Competition	RT	Position	Mean	Standard Deviation	N
CATT	Noise	Long	Final	64.82	13.59	22
			Initial	73.09	11.79	22
			Total	68.95	13.25	44
		Medium	Final	60.91	13.41	22
			Initial	68.55	14.46	22
			Total	64.73	14.31	44
		Short	Final	83.64	9.79	22
			Initial	89.09	8.57	22
			Total	86.36	9.50	44
		Total	Final	69.79	15.77	66
			Initial	76.91	14.66	66
			Total	73.35	15.58	132
	Quiet	Long	Final	69.27	8.59	22
			Initial	84.00	10.62	22
			Total	76.64	12.11	44
		Medium	Final	85.64	8.96	22
			Initial	93.64	8.16	22
			Total	89.64	9.38	44
		Short	Final	93.64	6.25	22
			Initial	98.36	2.94	22
			Total	96.00	5.39	44
		Total	Final	82.85	12.91	66
			Initial	92.00	9.85	66
			Total	87.42	12.33	132
	Total	Long	Final	67.05	11.46	44
			Initial	78.55	12.38	44
			Total	72.80	13.20	88
		Medium	Final	73.27	16.83	44
			Initial	81.09	17.20	44
			Total	77.18	17.37	88
		Short	Final	88.64	9.57	44
			Initial	93.73	7.88	44
			Total	91.18	9.08	88
		Total	Final	76.32	15.78	132
			Initial	84.45	14.57	132
			Total	80.39	15.70	264

Table 23. Continued.

Room Environment	Noise Competition	RT	Position	Mean	Standard Deviation	N
Lexicon	Noise	Long	Final	63.09	14.44	22
			Initial	78.36	13.04	22
			Total	70.73	15.64	44
		Medium	Final	90.73	8.32	22
			Initial	92.91	8.55	22
			Total	91.82	8.41	44
		Short	Final	93.82	4.57	22
			Initial	96.36	4.92	22
			Total	95.09	4.87	44
		Total	Final	82.55	17.04	66
			Initial	89.21	12.17	66
			Total	85.88	15.12	132
	Quiet	Long	Final	64.64	14.91	22
			Initial	84.55	7.54	22
			Total	74.59	15.42	44
		Medium	Final	97.64	5.33	22
			Initial	98.91	5.12	22
			Total	98.27	5.20	44
		Short	Final	97.64	3.19	22
			Initial	99.64	1.71	22
			Total	98.64	2.72	44
		Total	Final	86.64	18.17	66
			Initial	94.36	8.76	66
			Total	90.50	14.73	132
	Total	Long	Final	63.86	14.53	44
			Initial	81.45	10.98	44
			Total	72.66	15.56	88
		Medium	Final	94.18	7.74	44
			Initial	95.91	7.59	44
			Total	95.05	7.67	88
		Short	Final	95.73	4.35	44
			Initial	98.00	4.00	44
			Total	96.86	4.31	88
		Total	Final	84.59	17.66	132
			Initial	91.79	10.88	132
			Total	88.19	15.08	264

Table 23. Continued.

Room Environment	Noise Competition	RT	Position	Mean	Standard Deviation	N
Total	Noise	Long	Final	67.12	13.50	66
			Initial	77.00	12.57	66
			Total	72.06	13.91	132
		Medium	Final	69.03	19.33	66
			Initial	70.61	20.53	66
			Total	69.82	19.88	132
		Short	Final	82.82	14.41	66
			Initial	85.15	14.41	66
			Total	83.98	14.40	132
		Total	Final	72.99	17.35	198
			Initial	77.59	17.19	198
			Total	75.29	17.40	396
	Quiet	Long	Final	74.82	15.68	66
			Initial	84.36	9.22	66
			Total	79.59	13.68	132
		Medium	Final	89.45	8.75	66
			Initial	96.61	6.09	66
			Total	93.03	8.32	132
		Short	Final	94.97	5.22	66
			Initial	98.85	2.41	66
			Total	96.91	4.49	132
		Total	Final	86.41	13.71	198
			Initial	93.27	9.11	198
			Total	89.84	12.12	396
	Total	Long	Final	70.97	15.08	132
			Initial	80.68	11.59	132
			Total	75.83	14.27	264
		Medium	Final	79.24	18.13	132
			Initial	83.61	19.95	132
			Total	81.42	19.15	264
		Short	Final	88.89	12.40	132
			Initial	92.00	12.38	132
			Total	90.45	12.46	264
		Total	Final	79.70	17.00	396
			Initial	85.43	15.82	396
			Total	82.57	16.66	792

Table 24. Source table for the main effects and higher-order interactions from the four-way repeated measures ANOVA.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	150624.404	35	4303.554	47.178	.000
Intercept	5399133.414	1	5399133.414	59188.163	.000
RMDESIGN	12735.343	2	6367.672	69.806	.000
COMPET	41949.111	1	41949.111	459.868	.000
RT	28734.859	2	14367.429	157.503	.000
POSITION	6494.727	1	6494.727	71.199	.000
RMDESIGN * COMPET	13686.798	2	6843.399	75.021	.000
RMDESIGN * RT	26157.838	4	6539.460	71.689	.000
COMPET * RT	8378.798	2	4189.399	45.926	.000
RMDESIGN * COMPET * RT	3815.475	4	953.869	10.457	.000
RMDESIGN * POSITION	1518.576	2	759.288	8.324	.000
COMPET * POSITION	253.414	1	253.414	2.778	.096
RMDESIGN * COMPET * POSITION	58.677	2	29.338	.322	.725
RT * POSITION	1624.212	2	812.106	8.903	.000
RMDESIGN * RT * POSITION	2534.485	4	633.621	6.946	.000
COMPET * RT * POSITION	300.798	2	150.399	1.649	.193
RMDESIGN * COMPET * RT * POSITION	2381.293	4	595.323	6.526	.000
Error	68962.182	756	91.220		
Total	5618720.000	792			
Corrected Total	219586.586	791			

RMENV = room environment; COMPET = noise competition; POSITION = consonant position.

Table 25. Post-hoc analysis for room environment via Tukey's HSD.

(I) RMENVIRO	(J) RMENVIRO	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Actual	CATT	-1.27	.83	.281	-3.21	.68
	Lexicon	-9.07	.83	.000	-11.02	-7.12
CATT	Actual	1.27	.83	.281	-.68	3.21
	Lexicon	-7.80	.83	.000	-9.75	-5.85
Lexicon	Actual	9.07	.83	.000	7.12	11.02
	CATT	7.80	.83	.000	5.85	9.75

* The mean difference is significant at the .05 level.

Table 26. Post-hoc analysis for reverberation via Tukey's HSD.

(I) RT	(J) RT	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Long	Medium	-5.60	.83	.000	-7.55	-3.65
	Short	-14.62	.83	.000	-16.57	-12.67
Medium	Long	5.60	.83	.000	3.65	7.55
	Short	-9.02	.83	.000	-10.97	-7.07
Short	Long	14.62	.83	.000	12.67	16.57
	Medium	9.02	.83	.000	7.07	10.97

A.

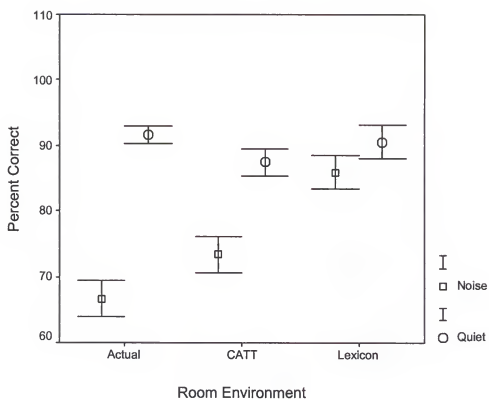


Figure 6. Ninety-five percent confidence intervals for the two-factor interaction of room environment and noise competition. A) Described by room environment. B) Described by noise competition.

B.

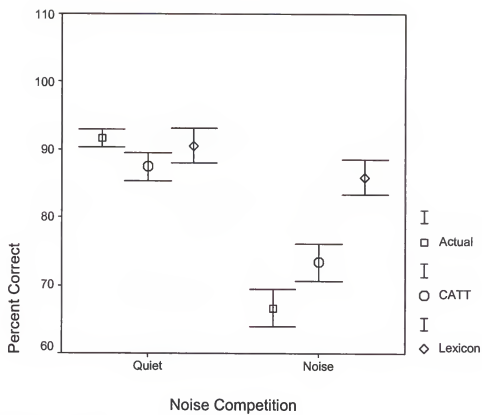


Figure 6. Continued.

A.

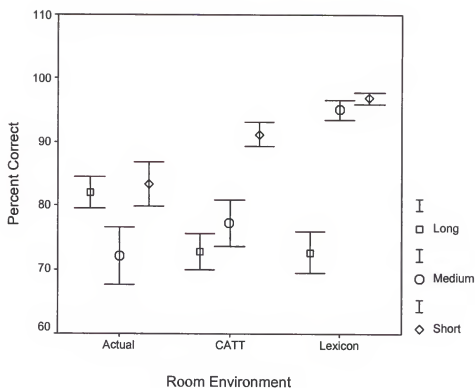


Figure 7. Ninety-five percent confidence intervals for the two-factor interaction of room environment and reverberation. A) Described by room environment. B) Described by RT.

B.

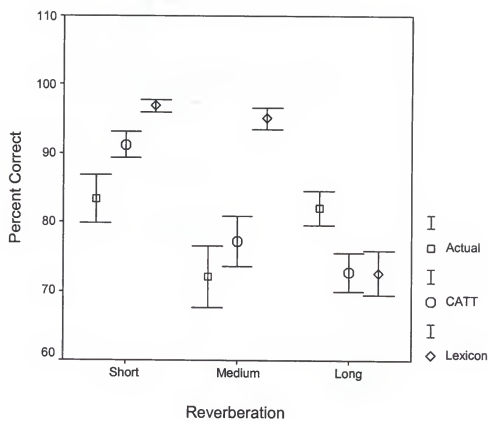


Figure 7. Continued.

A.

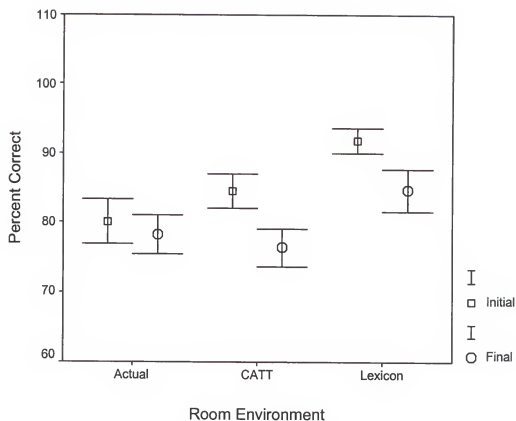


Figure 8. Ninety-five percent confidence intervals for the two-factor interaction of room environment and consonant position. A) Described by room environment. B) Described by consonant position.

B.

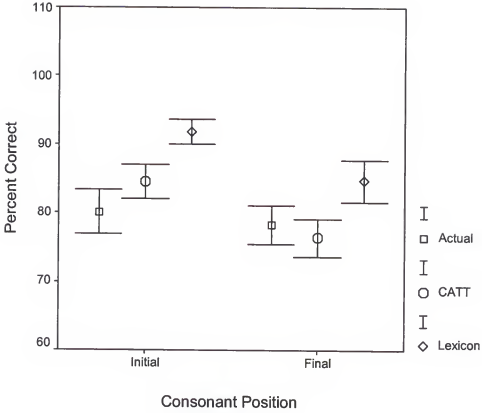


Figure 8. Continued.

A.

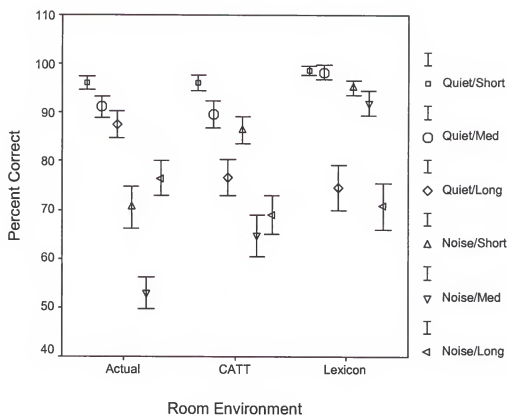


Figure 9. Ninety-five percent confidence intervals for the three-factor interaction of room environment, noise competition, and reverberation. A) Described by room environment. B) Described by noise competition. C) Described by RT.

B.

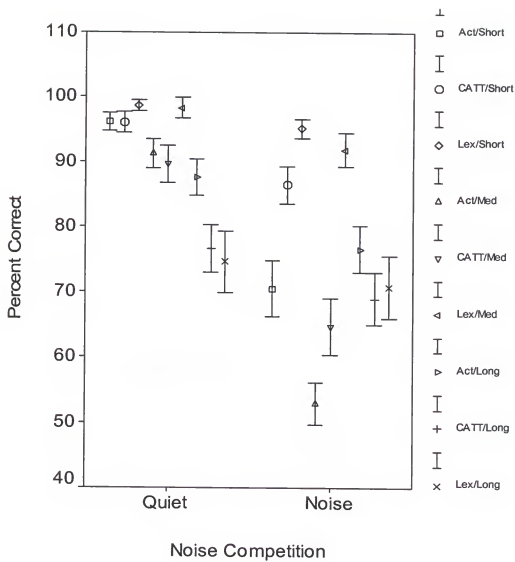


Figure 9. Continued.

C.

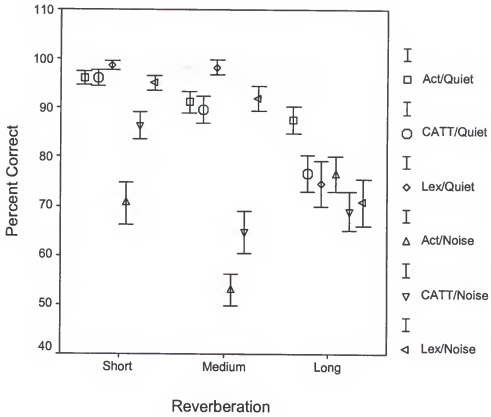


Figure 9. Continued.

A.

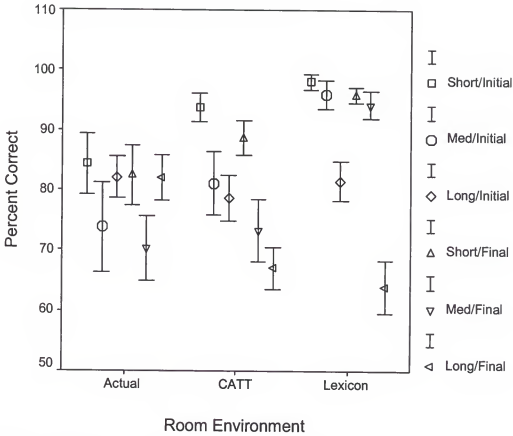


Figure 10. Ninety-five percent confidence intervals for the three-factor interaction of room environment, reverberation, and consonant position. A) Described by room environment. B) Described by RT. C) Described by consonant position.

B.

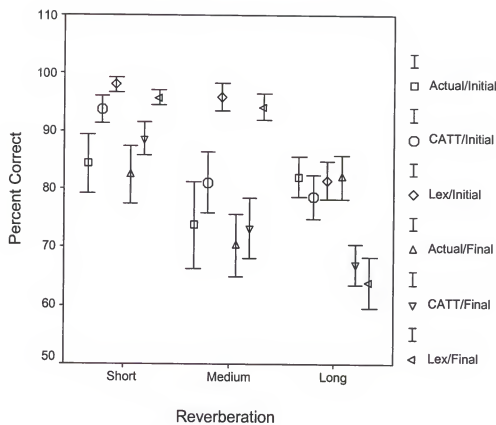


Figure 10. Continued.

C.

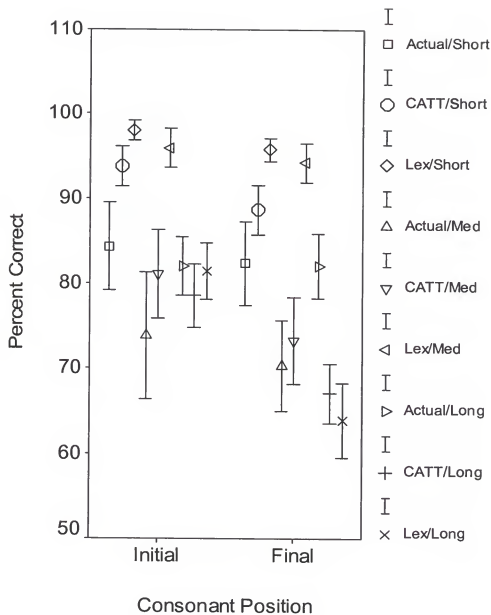


Figure 10. Continued.

A.

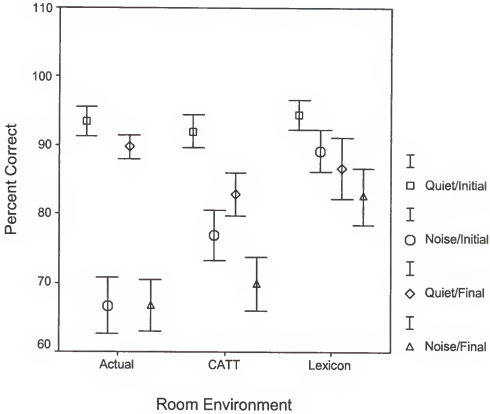


Figure 11. Ninety-five percent confidence intervals for the three-factor interaction of room environment, noise competition, and consonant position. A) Described by room environment. B) Described by noise competition. C) Described by consonant position.

B.

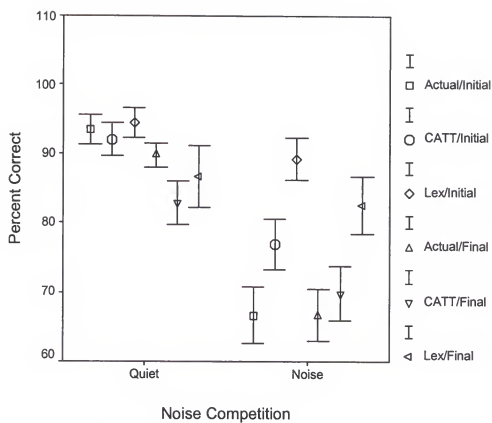


Figure 11. Continued.

C.

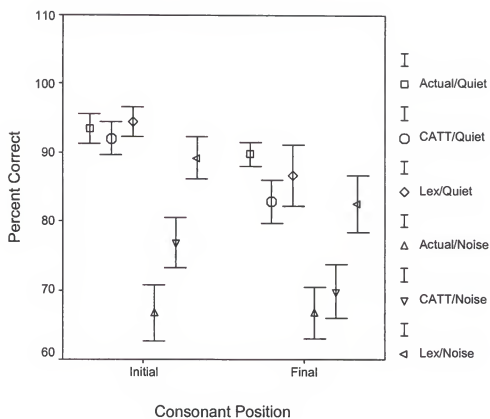


Figure 11. Continued.

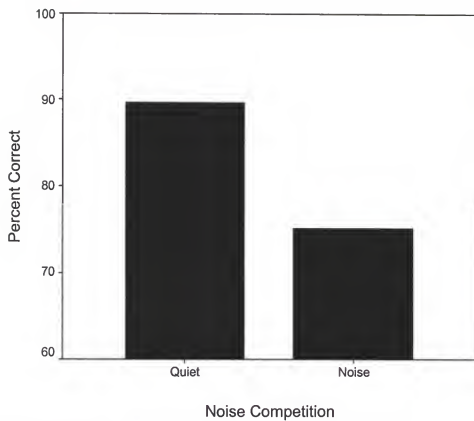


Figure 12. Mean speech-perception scores for noise competition.

A.

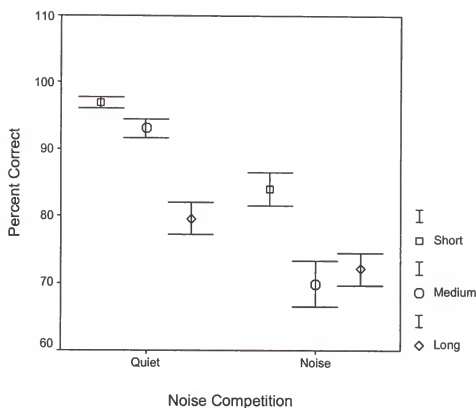


Figure 13. Ninety-five percent confidence intervals for the two-factor interaction of noise competition and reverberation. A) Described by noise competition. B) Described by RT.

B.

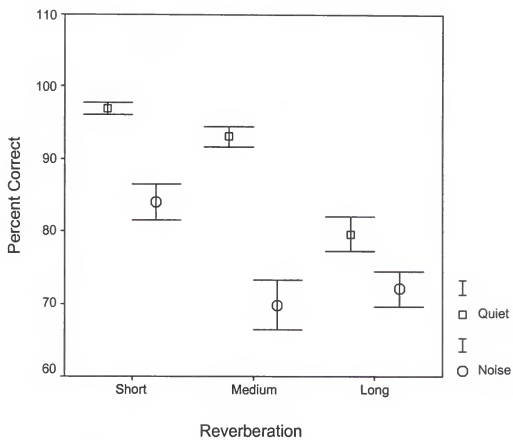


Figure 13. Continued.

A.

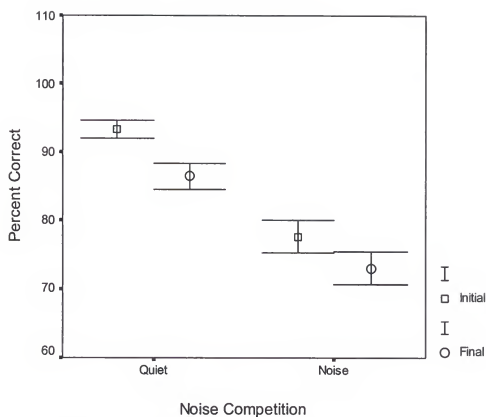


Figure 14. Ninety-five percent confidence intervals for the two-factor interaction of noise competition and consonant position. A) Described by noise competition. B) Described by consonant position.

B.

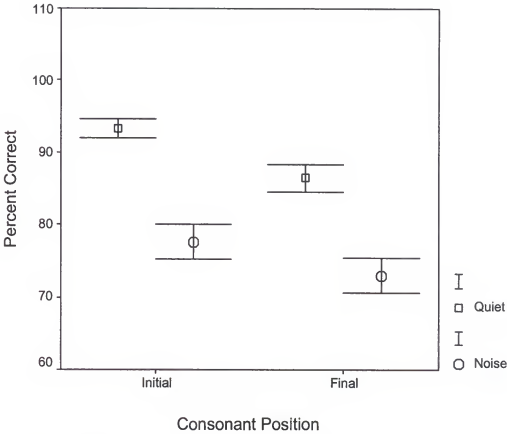


Figure 14. Continued.

A.

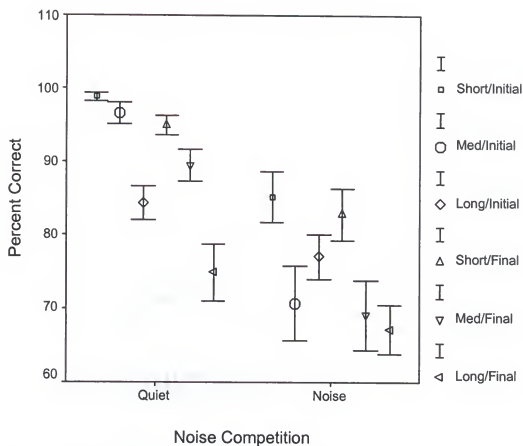


Figure 15. Ninety-five percent confidence intervals for the three-factor interaction of noise competition, reverberation, and consonant position. A) Described by noise competition. B) Described by RT. C) Described by consonant position.

B.

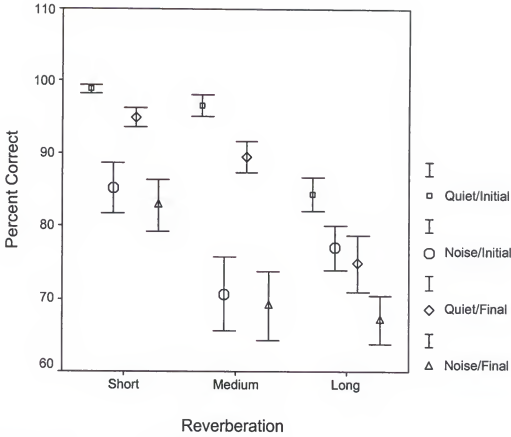


Figure 15. Continued.

C.

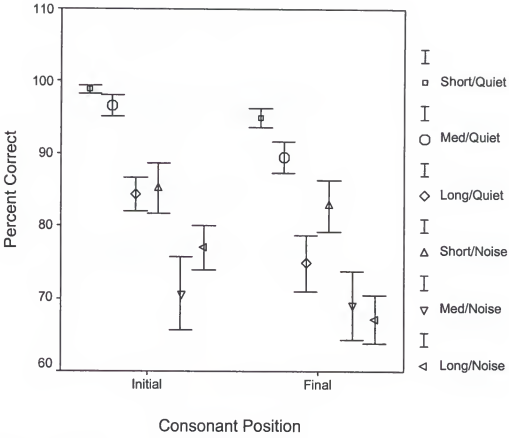


Figure 15. Continued.

A.

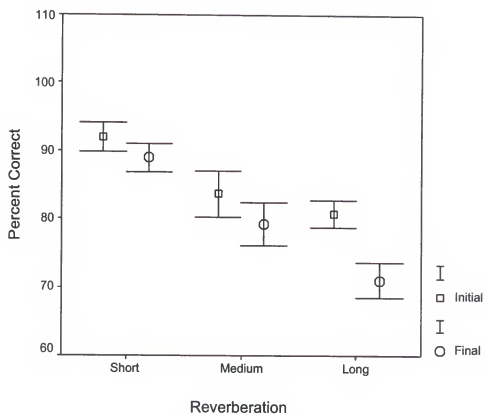


Figure 16. Ninety-five percent confidence intervals for the two-factor interaction of reverberation and consonant position. A) Described by RT. B) Described by consonant position.

B.

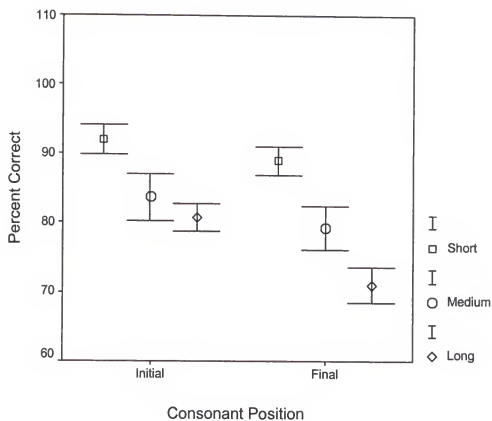


Figure 16. Continued.

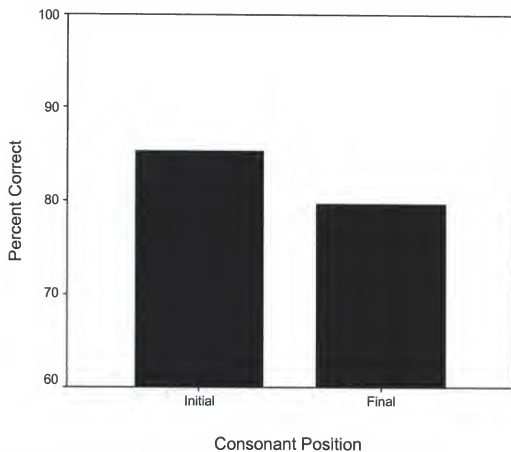


Figure 17. Mean speech-perception scores for consonant position.

CHAPTER 5 DISCUSSION

This study examined the effects of simulated reverberation on the speech-perception of adult listeners with normal hearing. Twenty-two adults who met the inclusion criteria listed in the methods section served as participants. The MRT served as the speech stimuli. Speech-spectrum noise served as the noise competition. For conditions that required added noise (in order to limit ceiling and floor effects), the noise was presented at a SNR of -10 dB for the short-RT and medium-RT rooms and at a SNR of 0 dB for the long-RT room. Simulated reverberation was achieved using via the CATT-Acoustic software program and the Lexicon MPX-550 Effects Processor. The speech-perception abilities of participants were tested in each of three actual rooms, which had different RTs (0.5, 1.3, and 5.3 seconds). Participants also were tested in a sound-treated booth for the CATT-Acoustic and Lexicon MPX-550 reverberation simulations of the rooms. The dependent variable for this study was speech-perception scores on the MRT. Analyses were conducted via a four-way repeated measures ANOVA procedure.

Overall, the major finding from this study is that the CATT-Acoustic simulations closely approximated the speech-perception abilities of adults with normal hearing in actual rooms. Conversely, the Lexicon MPX-550 simulations did not closely approximate speech perception in actual rooms. In addition to these findings, several additional trends were noted, including:

- (1) Speech-perception scores without added noise were better than speech-perception scores with added noise;
- (2) In general, increased reverberation resulted in decreased speech perception;
- (3) Reverberation appeared to affect the speech perception of final consonants more than the speech perception of initial consonants;
- (4) The addition of noise into the environment did not appear to affect the speech perception of initial or final consonants more than the other;
- (5) Actual room data supported the synergistic effect of reverberation and noise.

The remainder of this section will discuss these findings in greater detail. In addition, clinical implications and future directions are addressed.

Room Environment

The primary purpose of this research was to compare the effects of simulated reverberation to actual-room reverberation on speech perception. To date, it has not been demonstrated that speech perception under simulated reverberation could approximate speech perception in actual room settings. Only one previous investigation attempted to simulate reverberation for the purposes of evaluating speech perception (Nabelek and Robinette, 1978). As previously discussed in Chapter 2, the speech-perception scores for the simulated reverberation in this study did not approximate speech-perception scores obtained in actual rooms across various RTs. In the present investigation, the main effect of room environment was significant. This suggested that speech-perception scores were not the same in all of the room environments. Post-hoc analyses verified no difference in speech-perception scores between the actual room and the CATT-Acoustic simulation. However, the speech-perception scores for the Lexicon MPX-550 simulation were different than both the actual room and the CATT-Acoustic simulation speech-perception scores. These results implied that the CATT-Acoustic software program was effective in

approximating the reverberation of the actual room. Conversely, the Lexicon MPX-550 simulation did not provide a good approximation of speech-perception scores obtained in the actual room settings.

One possible explanation for these findings is that the Lexicon MPX-550, unlike the CATT-Acoustic program, does not have specific settings for absorption and diffusion coefficients of construction materials, the inclusion of various room furnishings, or the size and shape of the room. These conditions can affect the reverberation characteristics of a room. This lack of specificity for modeling an actual room likely contributed to the inability of the Lexicon MPX-550 to approximate the speech-perception scores of the actual room environments. Recall that the Lexicon MPX-550 Effects Processor is a stereo, hardware dual channel processor. The two channels can control different effects independently. For example, reverberation can be combined with delay, modulation, and pitch effects. The sound can be routed through a one-third octave graphic equalizer to simulate sound reflections or absorptions at particular frequencies for a given room surface more closely. In comparison, the CATT-Acoustic program is an impulse-response based acoustic measurement and simulation tool. The CATT-Acoustic program allows one to develop a three dimensional room design, assign absorption and scattering coefficients to the surfaces, locate listeners and sound sources in the room, and produce auralizations based on calculated binaural impulse responses. We are currently examining potential sources of variability to determine whether the Lexicon MPX-550 could simulate actual-room reverberation more closely with different user settings. In specific, we will be examining the temporal aspects of the Lexicon MPX-550 output via impulse-response measures. Recall that while we examined impulse responses with the

CATT-Acoustic simulations, only spectral information was analyzed with the Lexicon MPX-550. Therefore, it is possible that any difference between the simulations may be due to the experimental procedures used in this investigation.

The interaction of room environment and noise competition also was significant, which suggested that there was a difference in speech perception between conditions with and without added noise in at least one of the three room environments. In specific, the results suggested that speech-perception scores in quiet were better than speech-perception scores with added noise for all three room conditions. The finding that speech perception decreased with added background noise was not surprising and is consistent with past research (Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Nabelek and Mason, 1981; Harris and Reitz, 1985; Harris and Swenson, 1990; Johnson, 2000).

There was also a difference in speech-perception scores for at least one of the three RTs (0.5, 1.3, and 5.3 seconds) in at least one of the three room environments. These analyses suggested a trend that speech-perception scores decreased as reverberation increased. This trend is also consistent with previous studies (Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Nabelek and Robinette, 1978; Gelfand and Silman, 1979; Nabelek and Mason, 1981; Harris and Reitz, 1985; Nabelek and Letowski, 1985, 1986; Harris and Swenson, 1990; Leeuw and Dreschler, 1991; Johnson, 2000). Recall that reverberation causes masking of consonant sounds due to upward spread of masking by the vowel phonemes. The masking of consonant phonemes results in reduced speech perception, as consonants tend to account for the vast majority of speech perception. In addition, when speech is presented at a relatively rapid

rate, reverberation can fill the silence between words with reverberant energy and cause the sound at the end of one word to mask the beginning sound of the next word. Two exceptions to the trend of speech perception decreasing as a function of increasing reverberation were previously noted regarding the two-factor interaction of reverberation and room environment. Specifically, as RT was increased from 0.5 to 1.3 seconds, the speech-perception scores for the Lexicon MPX-550 simulation remained virtually the same, while the speech-perception scores decreased for the actual rooms and CATT-Acoustic simulation. A possible explanation for this phenomenon is that the Lexicon MPX-550 simulation for the medium-RT condition ($RT = 1.3$ seconds) was not sufficiently challenging relative to the actual room and CATT-Acoustic simulation. Once again, it is important to note that we are currently examining different Lexicon MPX-550 settings to determine if closer simulations of speech perception can be attained.

The other exception in which speech perception did not decrease as a function of increased RT was the speech-perception scores for the actual rooms were lower for the medium RT room than for the long-RT room. This exception is most likely explained by the difference in SNR between these two rooms. Recall that the SNR was -10 dB for the medium-RT room but the SNR was 0 dB for the long-RT room.

The interaction of room environment and consonant position also was significant, which suggested that there was a difference in speech perception between initial and final consonant positions in at least one of the three room environments. The results of this interaction suggested there was a greater difference between initial and final speech-perception scores for the CATT-Acoustic and Lexicon MPX-550 simulations (8.1% and 7.2%, respectively) than for the actual rooms (1.8%). Because this interaction is

collapsed across RT and noise condition, the difference between the simulations and the actual rooms may be explained by the synergistic effect of noise and reverberation on speech perception (Finitzo-Hieber and Tillman, 1978; Siebein et al., 1997; Johnson, 2000). This synergistic effect suggests that reverberation and noise when presented together have a more detrimental effect on speech perception than when either reverberation or noise is presented alone. As previously discussed, the different presentation methods of the noise competition may provide a sufficient explanation for the difference between the actual rooms and the simulations for initial and final consonant speech-perception scores. In the actual rooms, when the noise was introduced via loudspeakers into the environment, the noise became “reverberant noise” (just as the speech stimuli became reverberant). Recall from Chapter 2, reverberation not only can cause masking within words (i.e., final consonants particularly are masked), but also can cause “spectral smearing” between words, effectively masking the initial consonants. The masking of initial consonants due to spectral smearing could have occurred with the MRT, as words were presented within a carrier sentence rather than in isolation. Specifically, spectral energy from the carrier phrase preceding the MRT stimulus word may have filled in the silence between the word prior to the stimulus and the stimulus word and masked the initial consonant of the stimulus word. In contrast, the noise competition for the simulations was introduced via loudspeakers in a sound-treated IAC booth and was not processed through the reverberation simulation hardware or software. Stated differently, only the speech stimuli were reverberant in the simulations, which caused a decrease in final consonant speech perception due to the prolongation of the vowel sound and the upward spread of masking. However, in the actual rooms, both the

speech stimuli and the noise were reverberant. The reverberant noise caused a decrease in the initial consonant speech perception due to the spectral smearing of energy from the carrier phrase, as well as a decrease in final consonant speech perception due to the upward spread of masking from the prolongation of vowel energy. Future simulations will examine the effects of reverberant noise on speech perception.

Data also indicated that at least one room environment varied between conditions with and without added noise for at least one of the three different RTs. Several trends were suggested from analyzing these results. First, speech perception decreased with added noise for all room environments and RTs. As previously discussed, this finding was expected. Second, speech perception decreased as RT increased for conditions without and with added noise across room environments. A noteworthy exception to this trend was the speech-perception data for the medium-RT and long-RT actual room environments. Recall from the previous discussion that the speech-perception scores for the medium-RT actual room were lower than for the long-RT actual room. Third, these analyses suggest that in most conditions (5 of 6) the actual room environment was more closely approximated by the CATT-Acoustic simulation than by the Lexicon MPX-550 simulation. These conditions were short and medium RTs without and with added noise, and long RT without added noise. The only condition in which the speech-perception scores for the Lexicon MPX-550 better approximated the speech-perception scores in the actual room than did the CATT-Acoustic speech-perception scores was the long-RT with added noise condition.

The present investigation also found that initial and final consonant speech-perception scores were different for at least one room environment and at least one RT.

These results suggested two major trends. First, speech perception for initial consonants was better than speech perception for final consonants (means = 85.4% and 79.7%, respectively) for all room environments and RTs. Differences between the initial and final consonant speech perception were consistent with past investigations (Gelfand and Silman, 1979; Nabelek and Letowski, 1986). Second, for the CATT-Acoustic and Lexicon MPX-550 simulations, the differences between the initial and final consonant speech-perception scores are greater as RT increases. However, under the same listening conditions for the actual rooms the differences between the initial and final consonant speech-perception scores remain about the same. Recall that this interaction is collapsed across noise conditions. Thus, the differences in the presentation of the noise competition for the actual rooms versus the simulations may explain this trend. Specifically, due to the synergistic effects of reverberation and noise, the reverberant noise in the actual rooms may have increased the spectral energy between words and thus had a greater masking effect on initial consonants than did the non-reverberant noise presented in the simulations.

Data from this investigation also suggest that the initial and final consonant speech-perception scores do not vary as a function of noise competition for any of the room environments. Further aspects of this interaction may be analyzed by referring to the two-factor interactions of room environment and noise competition, room environment and consonant position, and noise competition and consonant position. Specifically, the interactions of room environment and noise competition, and room environment and consonant position were both significant. In contrast, the interaction of noise competition and consonant position was not significant, which suggested that the

speech perception of initial and final consonants did not vary as a function of noise condition. It can therefore be reasoned that the lack of significance for the present three-factor interaction may be explained by the lack of significance in the lower-order interaction (Agresti and Finlay, 1997). This interaction will be further discussed below.

Noise Competition

This study also examined the effect of noise on speech perception. Recall that noise was added because pilot data suggested that there would be ceiling effects for speech-perception scores in the 0.5-second and 1.3-seconds actual rooms. These data revealed that speech perception without added noise was better than speech perception with added noise. In specific, the mean speech-perception scores were 89.8% and 75.3% for conditions without and with added noise, respectively. From analyses of the interactions with noise competition, it is clear that speech perception in quiet was superior to speech perception in noise under all listening conditions. It is reasonable to speculate that speech perception decreased with added noise due to the masking effects of noise on speech. When speech is presented in noise, some parts of speech (particularly consonants) are masked by the noise. The trend that speech perception decreases with noise is consistent with past studies (Miller and Nicely, 1955; Pickett, 1957; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Nabelek and Mason, 1981; Harris and Reitz, 1985; Harris and Swenson, 1990; Nabelek and Nabelek, 1994; Johnson, 2000).

The interaction of noise competition and reverberation also was significant, which suggested that speech-perception scores without and with added noise were different for at least one RT. Results suggested a trend that speech perception without added noise

decreased significantly as RT increased from 0.5 to 1.3 to 5.3 seconds. Furthermore, speech perception in noise decreased significantly as RT increased from 0.5 to 1.3 seconds, but did not decrease as RT increased to 5.3 seconds. This finding may be explained by considering the presentation level of the noise competition in these conditions. Recall that the SNR for the 0.5- and 1.3-seconds RT was -10 dB, while the SNR for the 5.3-seconds RT was 0 dB, in an attempt to limit ceiling and floor effects, respectively. It is reasonable, therefore, to postulate that the speech-perception scores for the 5.3-seconds RT would have been considerably poorer if the SNR was -10 dB in that condition. The -10 dB SNR condition was attempted, but participants in the first row reported not being able to hear the speech stimulus at all. Hence, if the SNR of -10 dB was used, it is possible that the trend for conditions both with and without noise would be that speech perception decreased as reverberation increased. Previous investigations in which the SNR has remained consistent across RTs have shown a trend that speech perception decreases as RT increases (Moncur and Dirks, 1967; Niemoeller, 1968; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Gelfand and Silman, 1979; Harris and Reitz, 1985; Nabelek and Letowski, 1986; Olsen, 1988; Harris and Swenson, 1990; Leeuw and Dreschler, 1991; Johnson, 2000).

Speech-perception scores for initial and final consonants did not vary as a function of noise competition. In comparison to the conditions without added noise, initial and final consonant speech-perception scores decreased by essentially equal amounts in conditions with added noise. Specifically, with the addition of noise, initial consonant speech-perception scores decreased 15.7% and final consonant speech-perception scores decreased by about 13.4% (a 2.3% difference). The similarity between

the initial and final consonant speech perception in noise suggests that the noise competition does not cause differences in initial and final consonant speech perception. Stated otherwise, speech-spectrum noise reduces perception of consonants that have approximately the same fundamental frequency and intensity equally, regardless of the position of the consonant within the word. Instead, this difference can presumably be attributed to some other factor, most likely reverberation. Reverberation can cause masking of final consonant sounds due to upward spread of masking, because vowel phonemes generally are lower in frequency and more intense than consonant phonemes. These initial and final consonant speech perception findings in regard to noise and reverberation are consistent with previous literature (e.g., Crum, 1974; Nabelek and Pickett, 1974a, b; Harris and Reitz, 1985; Harris and Swenson, 1990; Johnson, 2000).

Data also suggest that there was no difference in the relative amount that initial and final consonant speech-perception scores change across the various RTs with noise added. Further aspects of this interaction were analyzed by examining the interactions of room environment and noise competition, noise competition and reverberation, noise competition and consonant position, and reverberation and consonant position. Specifically, the interactions of room noise competition and reverberation, and reverberation and consonant position were significant. However, the two-factor interaction of noise competition and consonant position was not significant, which suggested that the speech perception of initial and final consonants did not vary as a function of noise condition. Therefore, the lack of significance for the present three-factor interaction may be explained by the lack of significance of the noise competition and consonant position interaction (Agresti and Finlay, 1997). Stated differently, because

the noise competition affected both initial and final consonant speech perception equally, the three-factor interaction was not significant. These data suggest that some of the effects of reverberation on speech perception were masked by noise (i.e., the added speech-spectrum noise had an equal or greater masking effect than reverberation). Limited research has been conducted on initial and final consonant speech perception using reverberation only and reverberation plus noise conditions. For example, neither Gelfand and Silman (1979), nor Nabelek and Letowski (1986), studied a reverberation plus noise condition. Johnson (2000) found that adult listeners' mean consonant identification scores were the same for the reverberation only (mean = 55.4, s.d. = 9.7) and reverberation plus noise (mean = 55.4, s.d. = 11.2) conditions when speech was presented at 30 dB SL re: SRT. As the presentation level for speech increased, however, the mean for the reverberation plus noise condition decreased relative to the reverberation only condition. It should be noted, however, that Johnson (2000) used CVCV material and did not present separate data for initial and final consonants. Presumably, noise was a primary factor being tested in the present investigation which may explain why the simulated reverberation conditions were not as accurate when noise was added. Recall that when the noise stimuli were presented in the actual rooms it became reverberant noise, whereas the noise stimuli presented in the sound booth for the simulations was essentially non-reverberant. Future investigations with simulated reverberation will need to examine the effects of reverberant noise within the sound booth.

Reverberation

This research also evaluated the effects of reverberation on speech perception. The main effect of reverberation was significant, which suggested that speech perception was different for at least one of the three RTs. Post-hoc analyses indicated that all three RTs were significantly different from one another. The trend suggested that speech perception decreased as a function of increasing RT. This trend is consistent with past investigations (Moncur and Dirks, 1967; Niemoeller, 1968; Crum, 1974; Nabelek and Pickett, 1974a, b; Finitzo-Hieber and Tillman, 1978; Gelfand and Silman, 1979; Harris and Reitz, 1985; Nabelek and Letowski, 1986; Olsen, 1988; Harris and Swenson, 1990; Leeuw and Dreschler, 1991; Johnson, 2000).

The interaction of reverberation and consonant position was significant, which suggested that speech perception for initial and/or final consonants varied for at least one of the three RTs. The trend from these data suggested that increasing reverberation has a more detrimental effect on final consonant speech perception than on initial consonant speech perception (i.e., the final consonant speech perception decreases more than the initial consonant speech perception). In specific, as RT increased from 0.5 to 5.3 seconds, speech perception of final consonants decreased by 17.9%, whereas initial consonant speech perception decreased by only 11.3%. This trend is also consistent with previous research (Gelfand and Silman, 1979; Nabelek and Letowski, 1986) and was expected due to the well-recognized masking effects of reverberation on speech.

Consonant Position

This study also investigated the effect of room environment, noise competition, and/or reverberation on initial and final consonant speech perception. While all

interactions involving consonant position have been discussed previously, the discussion of whether the main effect of consonant position was significant also is important. Results suggested that there was a difference between initial and final consonant speech perception. Initial consonant speech perception was better than final consonant speech perception. Recall that Figure 17 shows the means for speech perception of initial consonants (85.4%) and final consonants (79.7%), collapsed across all other conditions. This trend is consistent with previous research (Gelfand and Silman, 1979; Nabelek and Letowski, 1986).

Clinical Implications

Prior studies have not demonstrated that simulated reverberation could impact speech-perception. Recall that all actual-room environments have reverberation; therefore, a test that would evaluate speech perception under various RTs, perhaps without and with added noise, would offer an assessment of how well the individual can perceive speech in a variety of actual environments. Because simulated reverberation has not been available clinically to audiologists, only two methods were available to measure speech perception under different RTs. One method was to measure speech perception in actual rooms with different RTs. The other method was to have one room that could be acoustically modified to change the RTs. Both of these methods are not clinically practical due to the time, cost, and/or difficulty moving and calibrating the equipment involved with these procedures.

In contrast, speech perception under the CATT-Acoustic simulation appears not to differ from speech perception in most actual room conditions. The use of the CATT-Acoustic program makes possible the modification of RTs of a virtual room while

keeping the same dimensions of the room. The CATT-Acoustic simulation may be used clinically to test speech perception under different RTs. A simulated reverberation CD may be made commercially available that would allow audiologists to change the RT simply by changing tracks on the CD. Speech-perception scores could be plotted as a function of RT, or an adaptive procedure might be used that would increase the RT if the individual responded correctly and decrease the RT if the individual responds incorrectly. More complex stimuli, such as sentences, would be useful to incorporate into such a test. A simulated reverberation test would be clinically useful in testing a variety of populations such as individuals with normal hearing, individuals with hearing loss, children, individuals with APD, and individuals who speak English as a second or other language (ESOL). In addition, such a test may be used to evaluate the benefit of directional hearing aid microphones in real-world conditions.

Limitations of this Study

This study has several potential limitations. First and foremost, this study was only able due to instrumentation limitations to examine the spectral output of the Lexicon MPX-550. As noted, it is possible that through more definitive analyses, and consequently more detailed instrument settings, that the Lexicon MPX-550 may more closely approximate speech perception obtained in actual reverberant rooms. Second, this study examined the effect of simulated reverberation on speech perception of individuals with normal hearing. Therefore, caution should be taken when attempting to interpolate results for other populations, such as individuals with hearing loss, children, individuals with APD, and individuals who speak English as a second or other language (ESOL). Third, only two simulations, the CATT-Acoustic software and the Lexicon

MPX-550 Effects Processor were examined. It is not known whether other methods of simulating reverberation for the purposes of speech perception may be appropriate. Fourth, this study used different actual rooms to test different RTs. The different acoustical characteristics of these particular rooms may have affected the results of the study. Ideally, a single room could be used in which the acoustical characteristics could be changed to alter RT. Fifth, different SNRs were used for the long-RT conditions than for the short-RT or medium-RT conditions. The use of different SNRs may have affected trends in the data; however, different SNR were used to eliminate potential floor effects in the long-RT room. Sixth, the noise competition for the simulated RT conditions was not processed through the CATT-Acoustic or Lexicon MPX-550. The difference in the noise competition may explain the differences in speech perception of initial and final consonants between the actual room and simulated conditions.

Future Research

This study provides the framework for much future research in the area of simulated reverberation and speech perception. First, future research will be conducted to examine potential sources of variance to explain why differences occurred between the two simulations. The following areas of variance will be examined: source (direction, pitch, loudness, location), receiver (direction relative to source, sensitivity), room (direct sound, early reflections, reverberation), and noise (method of presentation, level, and location). Further studies utilizing more detailed models via the CATT-Acoustic program and other pre-set or custom-user programs via the Lexicon MPX-550 Effects Processor may be conducted in an effort to get even better simulations of actual-room reverberations. A comparison of simulated reverberation with added noise that has not

been processed through the simulator (as in this study) and added noise that has been processed through the simulator would provide further insight on the results of the current study. Also, the use of more complex speech stimuli (i.e., sentences) could be incorporated into future studies. Additional projects will include examining the effect of simulated reverberation on speech perception of individuals with hearing impairment (unaided and aided), auditory processing disorders, children of different ages, etc. Simulated reverberation may also be used to test the benefit of directional of hearing aid microphones as well as frequency-modulation (FM) systems.

APPENDIX A
UNIVERSITY OF FLORIDA ADULT AUDIOLOGICAL CASE HISTORY FORM

ADULT AUDIOLOGICAL CASE HISTORY	
Name: _____	SS#: _____
Address: _____	Date of Birth: _____
City: _____	State: _____ Zip Code: _____ Age: _____
Phone: (H) _____ (W) _____	Other: _____
Referred by: _____	
Occupation: _____	Employer: _____
Name of person responsible for payment: _____	
Address (if different from above): _____	
Insurance carrier: _____	Policy #: _____
<u>STATEMENT OF THE PROBLEM</u>	
Why did you schedule today's evaluation? _____	
Do you think you have a hearing problem? ☐ Yes ☐ No ☐ Not sure	
If yes, which ear? ☐ Right ☐ Left ☐ Both	
Which do you feel is your better ear? ☐ Right ☐ Left	
When did you first notice a hearing problem? _____	
Has the hearing loss been: ☐ Gradual ☐ Sudden ☐ Fluctuating	
Have you had your hearing tested previously? ☐ Yes ☐ No ☐ Not sure	
If yes, where? _____ When? _____	
What were the results? _____	
Have you ever consulted an Ear, Nose, and Throat physician? ☐ Yes ☐ No ☐ Not sure	
If yes, which doctor? _____	
What was the reason for the visit? _____	
Is there a history of hearing loss in the family? ☐ Yes ☐ No ☐ Not sure	
If yes, which family members have a loss? _____	
What caused their hearing loss? _____	
<u>Check those which apply:</u>	
☐ Frequent ear infections ☐ Draining ears ☐ Sudden loss of hearing ☐ Ear pain, swelling or tenderness ☐ Fullness or pressure in the ears ☐ Head, neck or ear surgery ☐ Acoustic trauma (gunfire, firecrackers)	☐ Frequent colds, allergies or sinus problems ☐ Headaches ☐ Visual problems (glaucoma, cataracts, glasses) ☐ Heart trouble ☐ Blood pressure problems ☐ Diabetes ☐ Skull trauma/loss of consciousness

Figure 18. The University of Florida Adult Audiological Case History Form.

Please indicate which of the following you have had:

- | | | |
|--|--|--|
| ☐ Measles | ☐ Hep B | ☐ Jaundice |
| ☐ Mumps | ☐ CMV | ☐ Epilepsy |
| ☐ Pneumonia | ☐ Severe Burns | ☐ Speech/language problems |
| ☐ Meningitis | ☐ Polio | ☐ Cancer (describe: _____) |
| ☐ TB (Tuberculosis) | ☐ Stroke | ☐ AIDS (HIV+) |
| ☐ Cerebral Palsy | ☐ Herpes | ☐ Rheumatic fever |
| ☐ High fever | ☐ RH (-) factor | ☐ Bacterial/fungal infection |
| ☐ Scarlet fever | ☐ Rubella | ☐ Kidney problems (describe: _____) |
| ☐ Chicken Pox | ☐ Malaria | ☐ Other (explain: _____) |
| ☐ Shingles | ☐ Diphtheria | ☐ _____ |

Please list any medications you take regularly: _____

Have you had/do you have problems with dizziness? ☐ Yes ☐ No ☐ Not sure

If yes, please check those that apply and answer the questions below:

- | | |
|---|--|
| ☐ I feel lightheaded. | ☐ I feel off-balance in space. |
| ☐ I feel like I'm going to fall. | ☐ The room is spinning and I'm still. |
| ☐ I feel sick to my stomach. | ☐ I feel like I'm spinning and the room is still. |
| ☐ Other (describe): _____ | |

When did you start feeling dizzy? _____

Is your dizziness caused by any particular body movement? _____

Have you consulted a physician about this problem? _____

Have you had/do you have problems with tinnitus (noise in the ears)? ☐ Yes ☐ No ☐ Not sure

If yes, please describe the type of noise: _____ Which ear? ☐ Right ☐ Left ☐ Both

How often? _____ How loud? _____

Do you have a history of exposure to loud noise? ☐ Yes ☐ No ☐ Not sure

If yes, please describe the type of noise and how long you were/have been exposed? _____

Have you been exposed to noise within the last 14 hours? ☐ Yes ☐ No ☐ Not sure

Did you wear hearing protection? ☐ Yes ☐ No ☐ Not sure

Do you have trouble hearing in any of the following situations:

- | | |
|---|---|
| ☐ On the telephone? | ☐ At school? ☐ At work? |
| ☐ Watching television? | ☐ At home? |
| ☐ Women's voices? | ☐ With background noise? |
| ☐ Men's voices? | ☐ At concerts/theater? |
| ☐ Children's voices? | ☐ At parties/social groups? |
| ☐ At the movies? | ☐ At religious services? |

Figure 18. Continued.

Which ear do you use on the telephone? ☐ Right ☐ Left
 Have you ever, or do you currently wear hearing aids? ☐ Yes ☐ No
 If yes, when did you first start wearing hearing aids? _____
 Do you wear hearing aids now? ☐ Yes ☐ No
 Which ear(s)? ☐ Right ☐ Left ☐ Both
 Brand: _____ Model: _____
 When did you get it? _____ Who recommended it? _____
 How many hours a day do you wear it? _____
 Are you/were you satisfied with it? ☐ Yes ☐ No If no, explain: _____

 Additional comments: _____

University of Florida Speech and Hearing Clinic
 435 Dauer Hall
 University of Florida
 Gainesville, FL 32611
 (352) 392-2041

I authorize the above named agency to secure and/or release information for professional use.

I also authorize release of information and necessary data pertinent to the filing of insurance claims, request payment of benefits to the party who accepts assignment (if applicable).

Clinical services in Speech and Hearing relate to training programs in these areas. We will appreciate willingness to sign the following statement:

"I agree to permit University Trainees, enrolled in pertinent academic training program participate in the evaluation and/or treatment procedures which will be conducted under the supervision of the faculty of the Clinical Training Programs. In addition, I agree to permit the use of closed-circuit television, the taking of photographs or motion pictures and other recording or similar graphic material which are to be used for teaching or scientific purposes."

Name: _____

SIGNATURE _____ DATE _____

Figure 18. Continued.

APPENDIX B MODIFIED RHYME TEST WORDS

Table 27. The 300 words of the Modified Rhyme Test.

List A	List B	List C	List D	List E	List F
rang	fang	gang	bang	sang	hang
hark	dark	mark	lark	park	bark
peel	reel	feel	heel	keel	ceel
tab	tan	tam	tang	tack	tap
sing	sit	sin	sip	sick	sill
map	mat	math	man	mass	mad
pun	puff	pup	pug	putt	pub
top	hop	pop	cop	mop	shop
nest	vest	west	test	best	rest
cut	cub	cuff	cup	cud	cuss
sake	sale	save	sane	safe	same
bust	just	rust	must	gust	dust
hear	heath	heal	heave	heat	heap
dig	dip	did	dim	dill	din
book	took	shook	cook	hook	look
sad	sass	sag	sack	sap	sat
sun	nun	gun	fun	bun	run
page	pane	pace	pay	pale	pave
hot	got	not	pot	lot	tot
kick	lick	sick	pick	wick	tick
kit	bit	fit	sit	wit	pit
kith	king	kid	kit	kiss	kill
foil	coil	boil	oil	toil	soil
jig	wig	big	rig	pig	fig
peace	peas	peak	peal	peat	peach
pill	pick	pip	pig	pin	pit
sud	sum	sub	sun	sup	sung
fill	fig	gin	fizz	fib	fit
dent	bent	went	tent	rent	sent
pass	pat	pang	pad	path	pan
teach	tear	tease	teal	team	teak
duck	dud	dull	dub	dug	dun
bean	beach	beat	beam	bead	beak
way	may	say	gay	day	pay
ten	pen	den	hen	then	men
raw	paw	law	jaw	thaw	saw
late	lake	lay	lace	lane	lame
gale	male	tale	bale	sale	pale
will	hill	kill	till	fill	bill
led	shed	red	bed	fed	wed
sold	told	hold	fold	gold	cold
bun	bus	but	buff	buck	bug
seep	seen	seethe	seed	seem	sock
pin	sin	tin	win	din	fin
meat	feat	heat	seat	beat	neat
fame	same	came	name	tame	game
sip	rip	tip	dip	hip	lip
bat	bad	back	bass	ban	bath
came	cape	cane	cake	cave	case
rave	rake	race	rate	raze	ray

APPENDIX C NOISE SPECTRA FOR ACTUAL ROOMS AND SIMULATIONS

A.

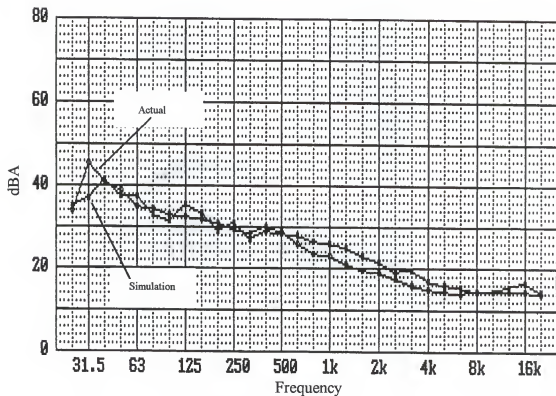


Figure 19. Comparison of actual room and simulation noise spectra for the conditions without added noise. A) Short RT. B) Medium RT. C) Long RT.

B.

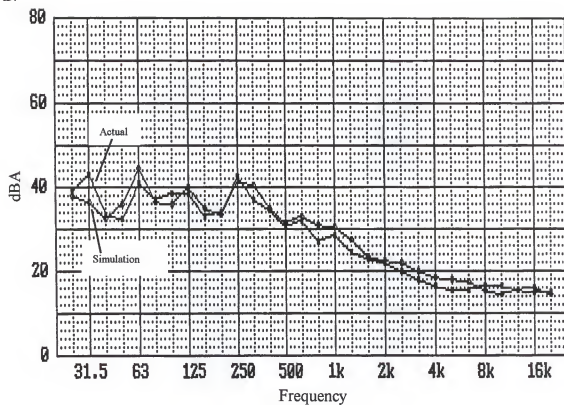


Figure 19. Continued.

C.

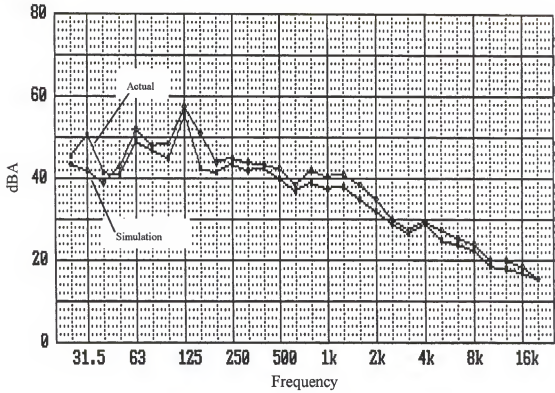


Figure 19. Continued.

A.

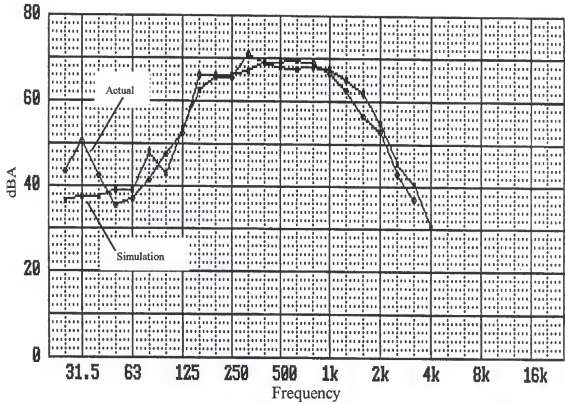


Figure 20. Comparison of actual room and simulation noise spectra for the conditions with added noise. A) Short RT. B) Medium RT. C) Long RT.

B.

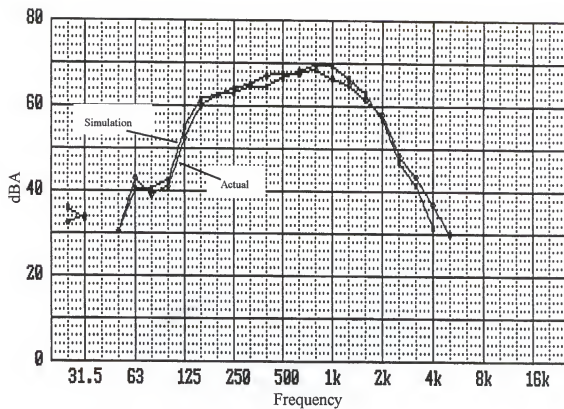


Figure 20. Continued.

C.

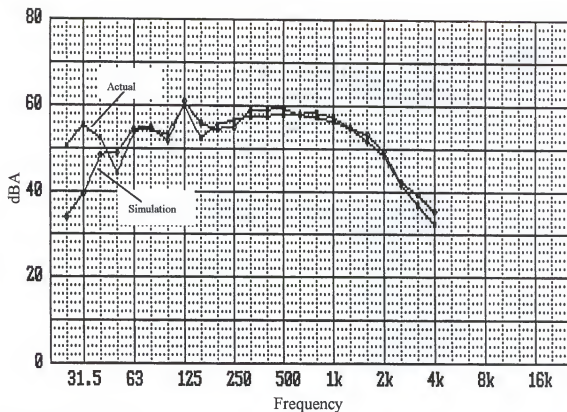


Figure 20. Continued.

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BIOGRAPHICAL SKETCH

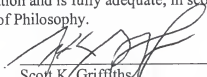
Brian Matthew Kreisman was born and raised in St. Louis, Missouri. He earned a Bachelor of Science in Communication Disorders from Saint Louis University. He earned a Master of Arts in Theological Studies with a Counseling Concentration from Covenant Theological Seminary. He earned a Master of Science in Speech and Hearing Sciences from Washington University in St. Louis. He began his doctoral work at the University of Florida in August 2000, where he has also taught undergraduate courses and supervised Doctor of Audiology (Au.D.) students in the University of Florida Speech and Hearing Clinic.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



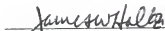
Carl C. Crandell, Chair
Associate Professor of
Communication Sciences and Disorders

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Scott K. Griffiths
Associate Professor of
Communication Sciences and Disorders

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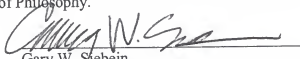
James W. Hall III
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This thesis was submitted to the Graduate Faculty of the Department of Communication Sciences and Disorders in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 2003

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